Measuring Transverse Quark Polarization with Spin Dependent Fragmentation Functions at

and

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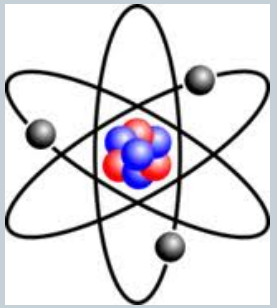
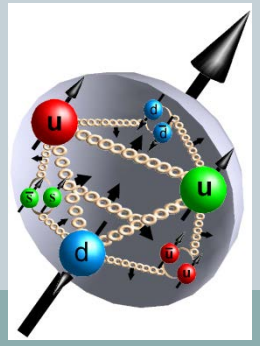
Outline

- Motivation: Measuring Transversity of the Nucleon
  - Transversity
  - Need for transverse spin dependent fragmentation functions for quark polarimetry
- Transverse spin dependent Fragmentation Function measurement in e^+-e^- annihilation at Belle
  - The Belle Experiment
  - Recent Results for di-Hadron Interference Fragmentation Function
  - Extraction of Transversity
- Outlook
  - Future Fragmentation Function measurements at Belle I+II

Motivation for Studying Spin Proton Structure & Quantum Chromo Dynamics

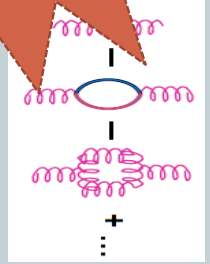
- QCD successful in describing high energy reactions
- **BUT** No consistent description of hadronic sector
  - →No consistent description of fundamental bound state of the theory
  - QCD binding energy : most of the visible mass in the universe
  - Spin is fundamental Quantum Number: What role does it play? Use transverse spin as precision probe.



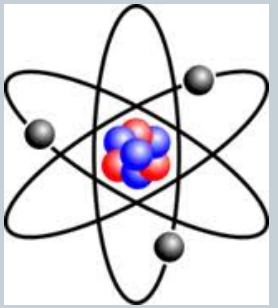


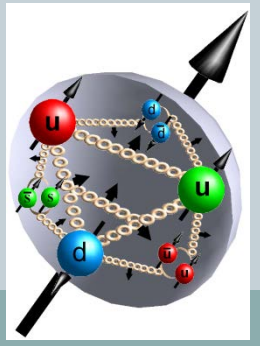
Motivation for Studying Spin Proton Structure & Quantum Chromo Dynamics

Millenium Prize



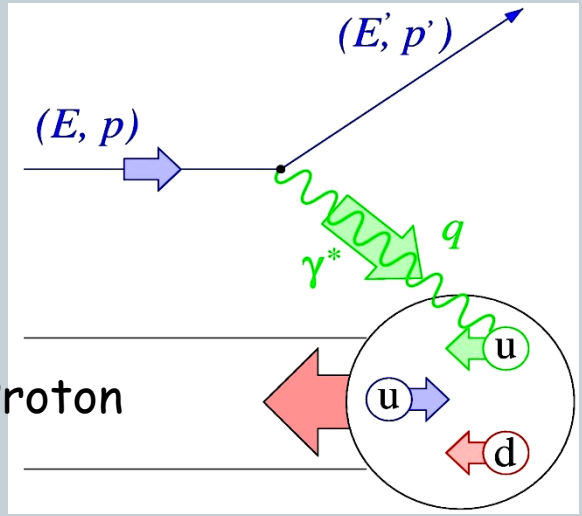
- QCD successful in describing high energy reactions
- **BUT** No consistent description of hadronic sector
  - →No consistent description of fundamental bound state of the theory : proton
  - QCD binding energy : most of the visible energy in the universe
  - Spin is fundamental Quantum Number: What role does it play? Use transverse spin as precision probe
- Compare to QED:
  - Bound state: QED: atom
  - Stringent tests of QED from study of spin structure of hydrogen
    - Lamb shift (Nobel prize 1955)
  - →Atomic physics, QCD?

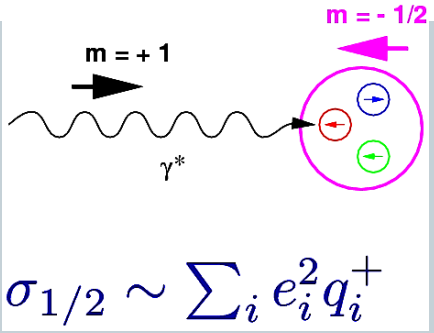




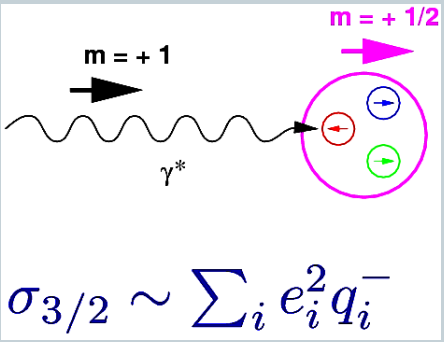
Probes to Study Polarized Proton Structure

Inclusive polarized deep inelastic scattering (DIS)





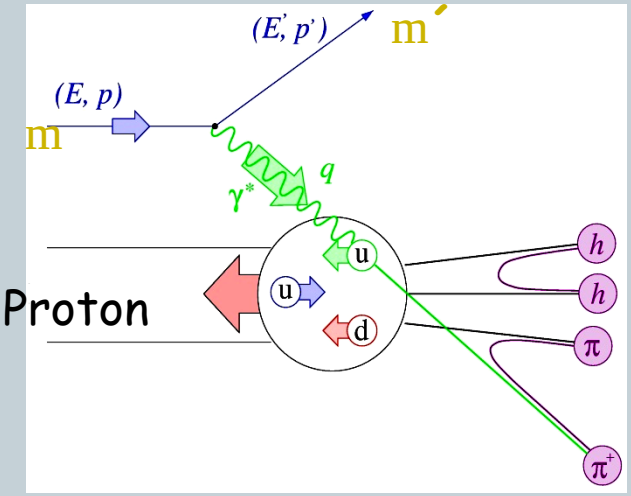
$$\sigma_{1/2} \sim \sum_i e_i^2 q_i^+$$

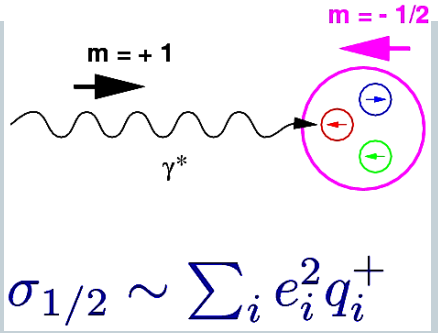


$$\sigma_{3/2} \sim \sum_i e_i^2 q_i^-$$

Probes to Study Polarized Proton Structure

Semi-Inclusive polarized deep inelastic scattering (DIS)





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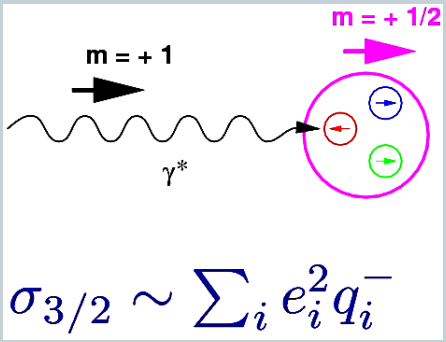
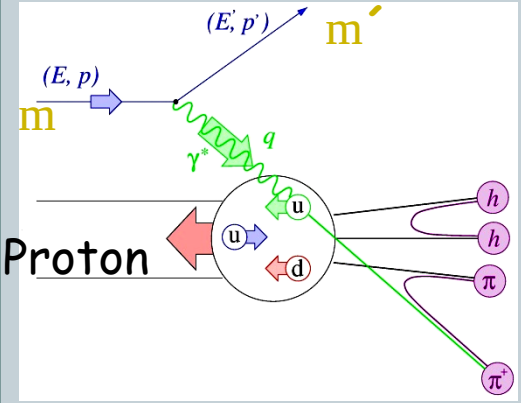


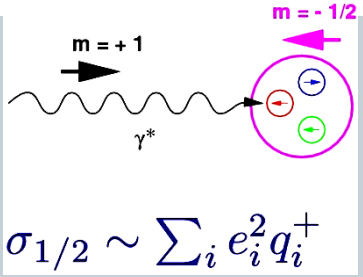
$$\sigma_{3/2} \sim \sum_i e_i^2 q_i^-$$

Fragmentation Process:
Outgoing quark forms hadrons

Probes to Study Polarized Proton Structure

(semi) Inclusive polarized deep inelastic scattering (DIS)





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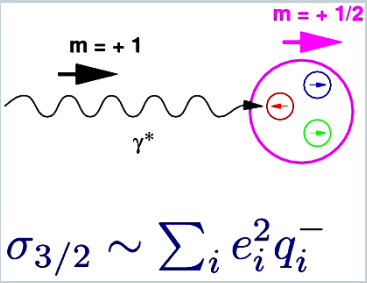
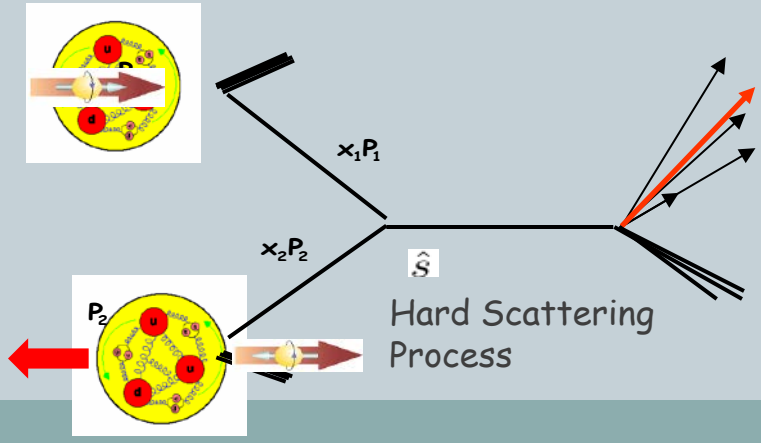
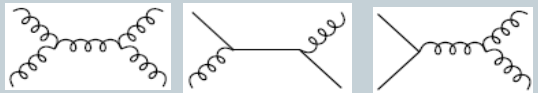


$$\sigma_{3/2} \sim \sum_i e_i^2 q_i^-$$

polarized pp scattering





ΔG^2 $\Delta G \Delta q$ Δq^2

Dominates at RHIC

Parton Distribution Functions

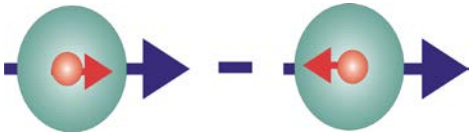
The three leading order, collinear PDFs

$f_1^q(x)$ 

unpolarized PDF

quark with momentum $x=p_{quark}/p_{proton}$ in a nucleon

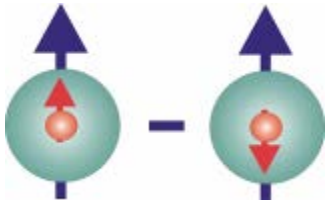
well known – unpolarized DIS

$g_1^q(x)$ 

helicity PDF

quark with spin parallel to the nucleon spin in a longitudinally polarized nucleon

known – polarized DIS

$h_1^q(x)$ 

transversity PDF

quark with spin parallel to the nucleon spin in a transversely polarized nucleon

Helicity – transversity: measurement of the nonzero angular momentum components in the protons wavefunction

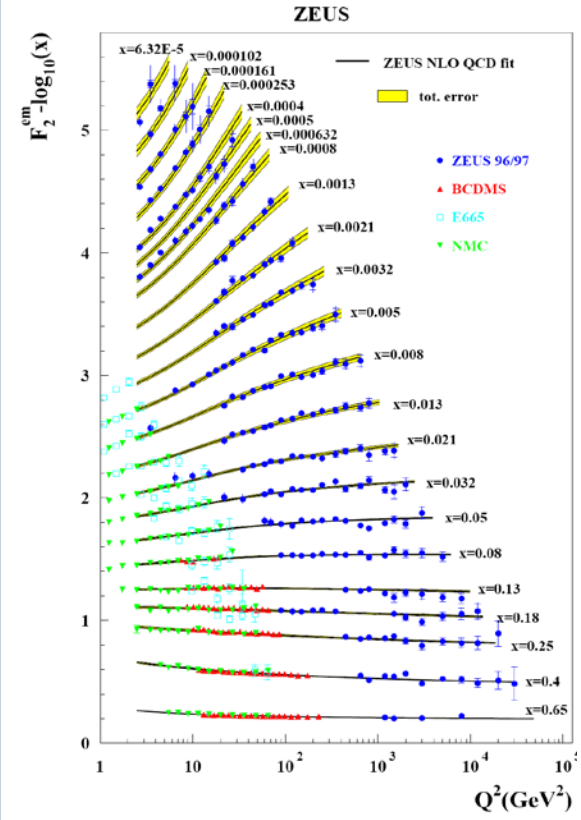
chiral odd, poorly known

Cannot be measured inclusively

Current Status of Distribution Functions

$$f_1 = \bullet$$

Unpolarized

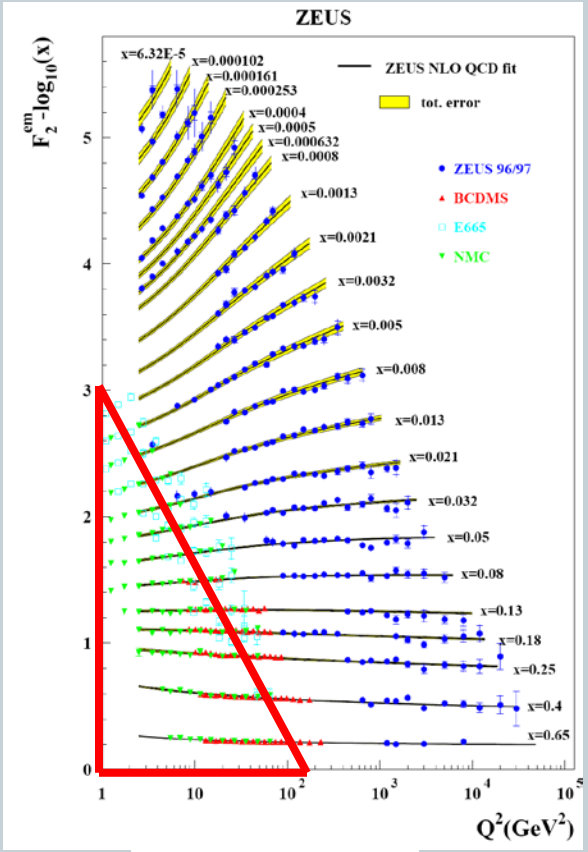


$$F_2 \propto \sum_q e^q f_1{}^q$$

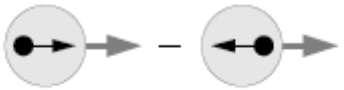
Current Status of Distribution Functions

$f_1 =$ 

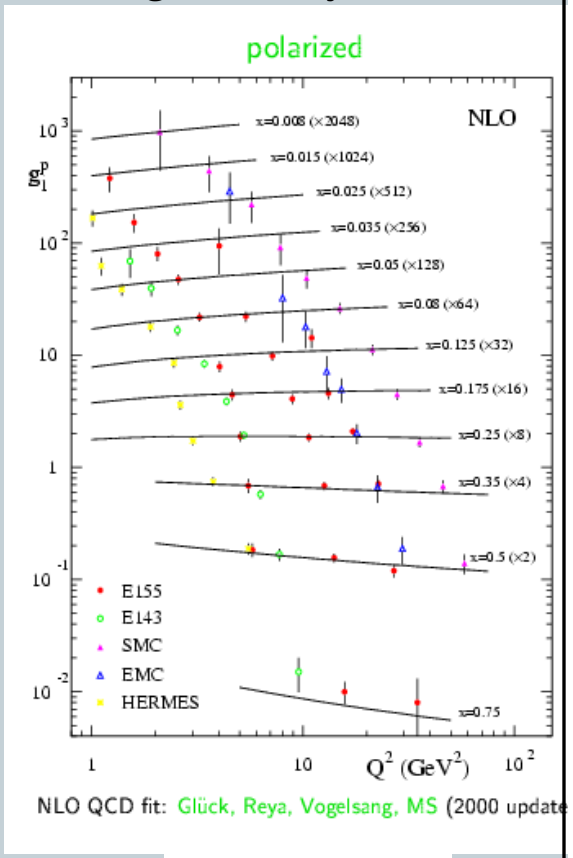
Unpolarized



$$F_2 \propto \sum_q x e_q^2 f_1{}^q$$

$g_1 =$ 

Longitudinally Polarized



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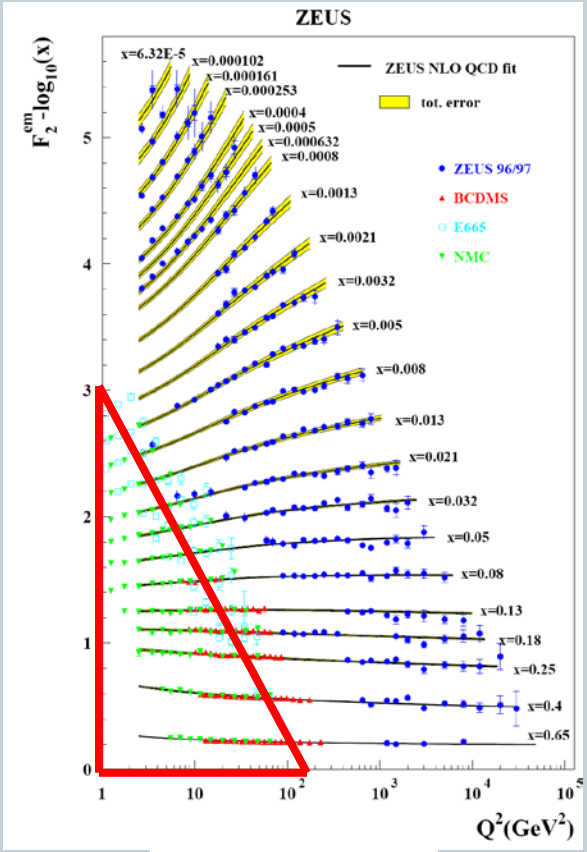

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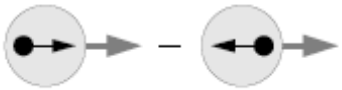
$g_1 =$ 

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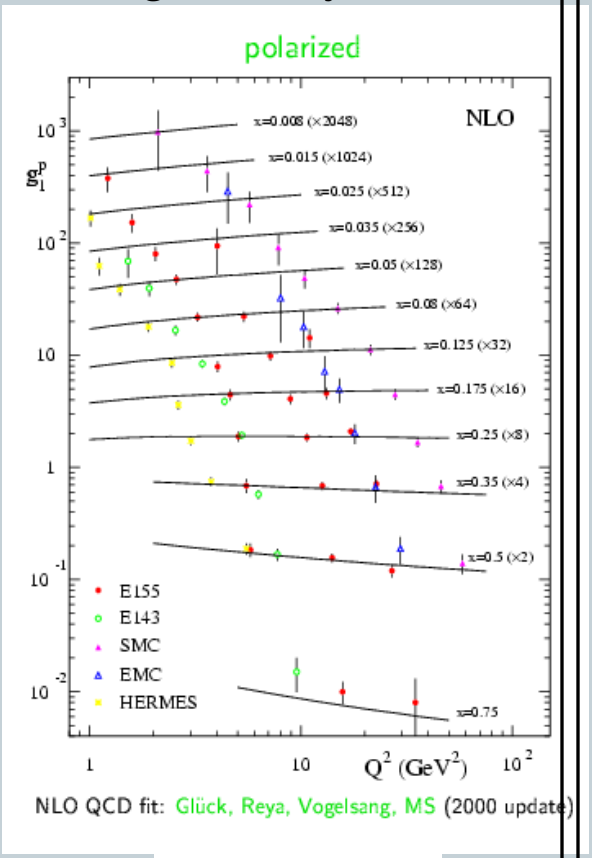

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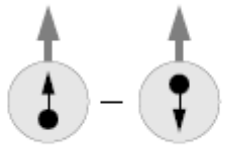
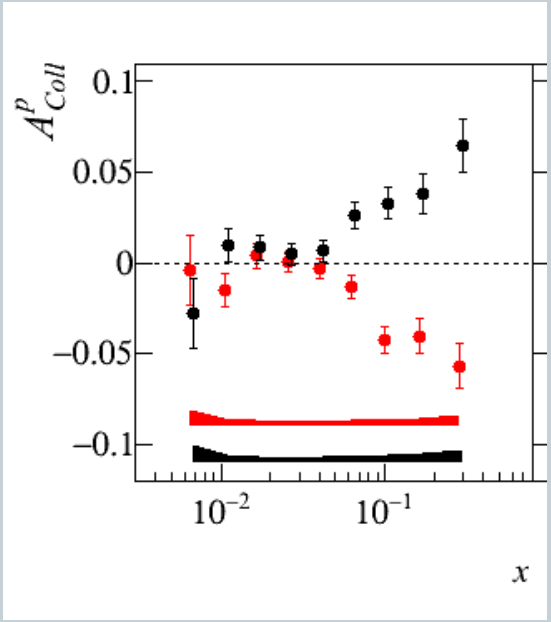
$h_1 =$ 

Transversely Polarized



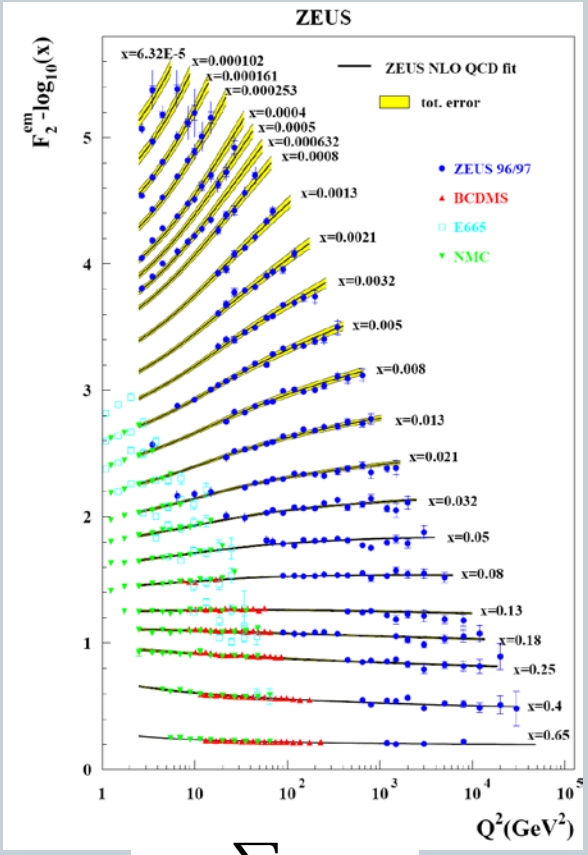
$$A^{Collins} \propto \frac{\sum_q e_q^2 h_1^q(x) * H_1^\perp}{\sum_q e_q^2 q_1^q(x) D_q^h(z)}$$

Chiral odd -
cannot be measured inclusively

Current Status of Distribution Functions

$f_1 =$ 

Unpolarized



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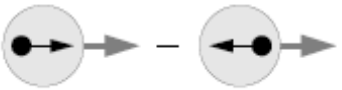
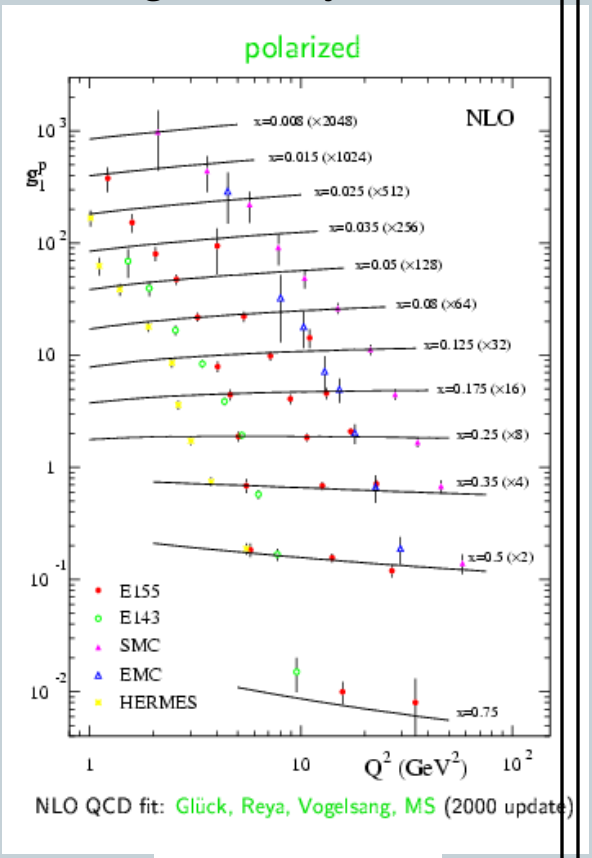
$g_1 =$ 

Longitudinally Polarized



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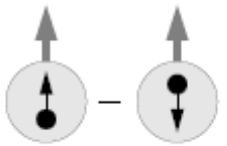
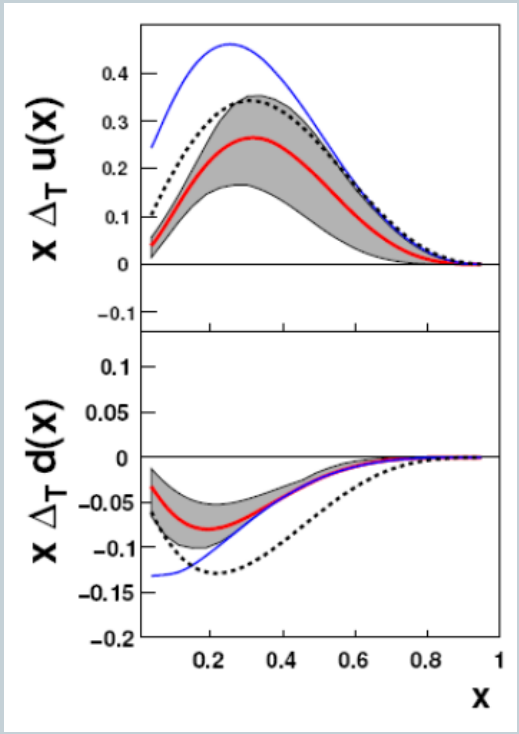
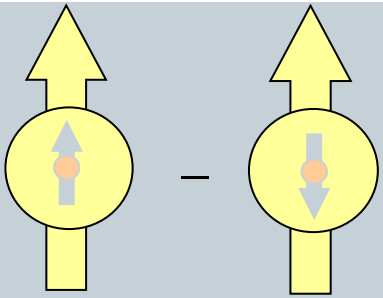
$h_1 =$ 

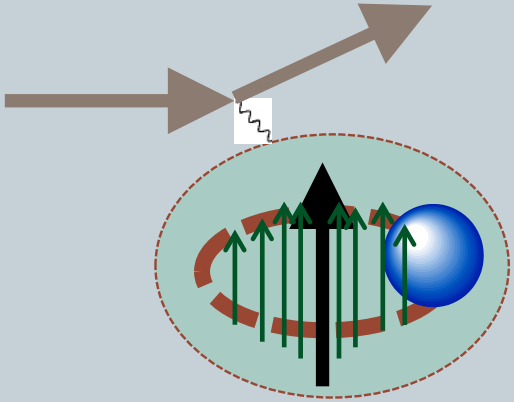
Transversely Polarized

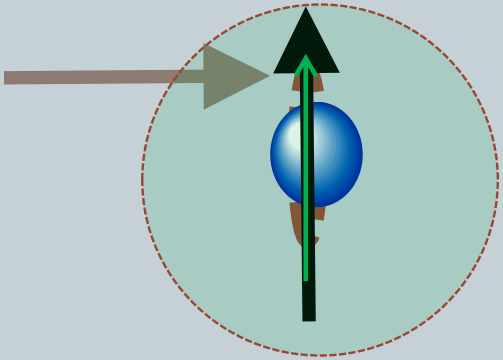


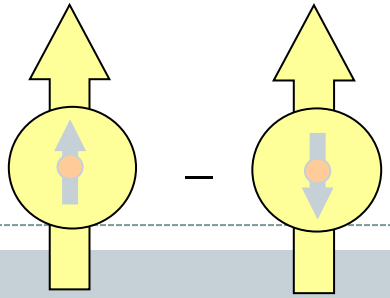
Transversity:

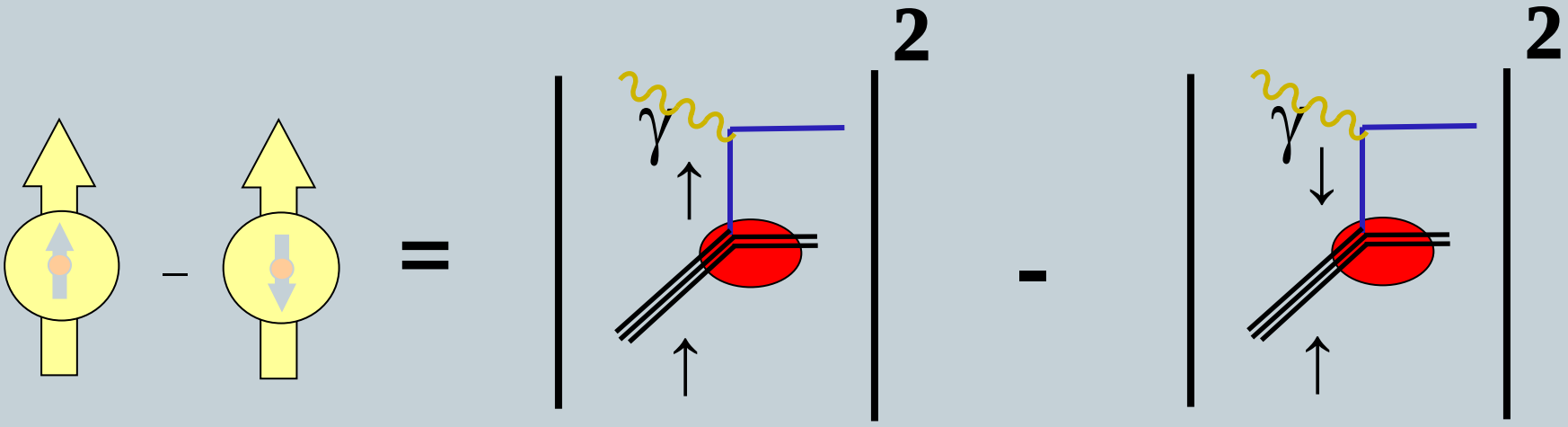
Why is  so hard to measure?

- Naïve picture: leptonic probe too ‘fast’ to be sensitive to transverse polarization





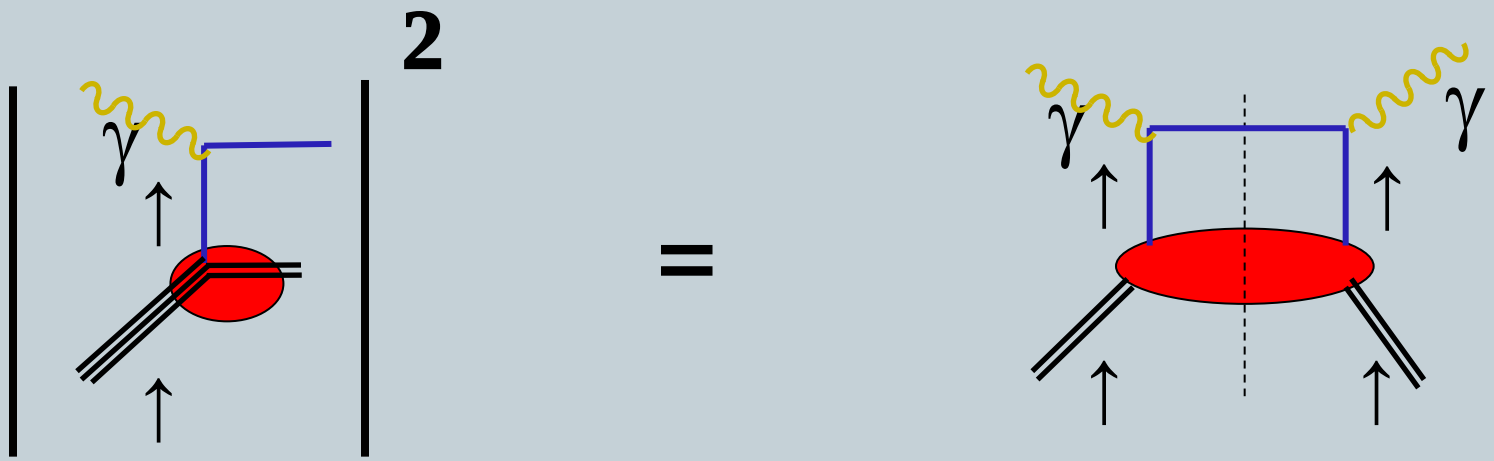
Why is  so hard to measure?



Probability of finding ↑ quark

Probability of finding ↓ quark

Handbag Diagrams

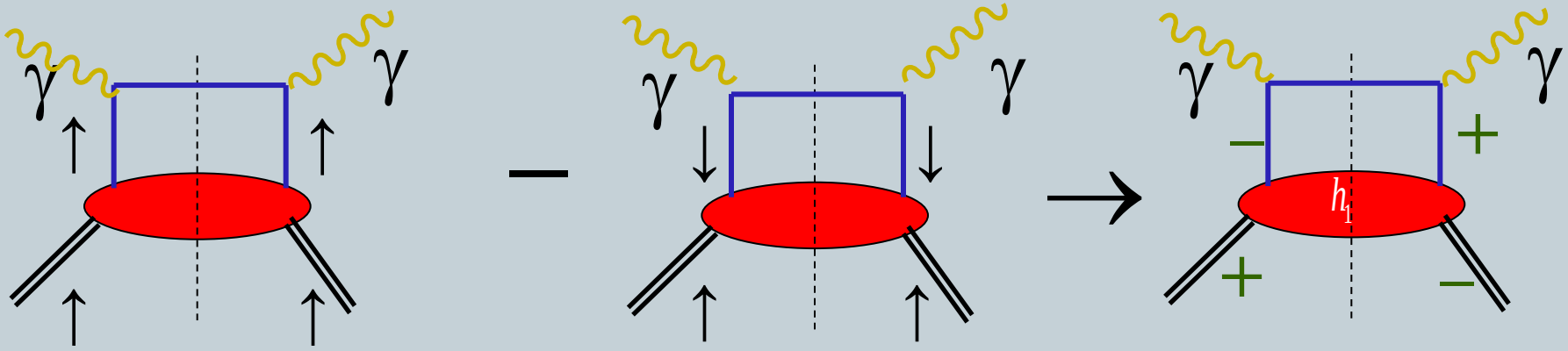


Optical Theorem:

$\sigma = -Im(A_{\text{forward scattering}})$

Transversity is Chiral Odd

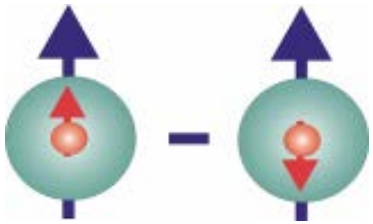
- Transversity base:



- **Helicity base**: chiral odd
- Needs chiral odd partner➔Fragmentation Function
- Does not couple to gluons ⇨different QCD evolution than $g_1(x)$
- Dominated by Valence Region

Importance of Transversity

$h_1^q(x)$

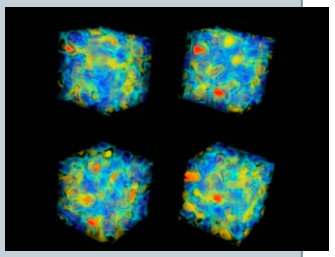


$$\frac{1}{2} = \frac{1}{2}\sum_{q,\bar{q}} \int dx h_q(x) + \sum_{q,\bar{q},G} \langle L_{s_T} \rangle$$

Baker, Leader, Trueman:
Transverse Polarization Sum Rule

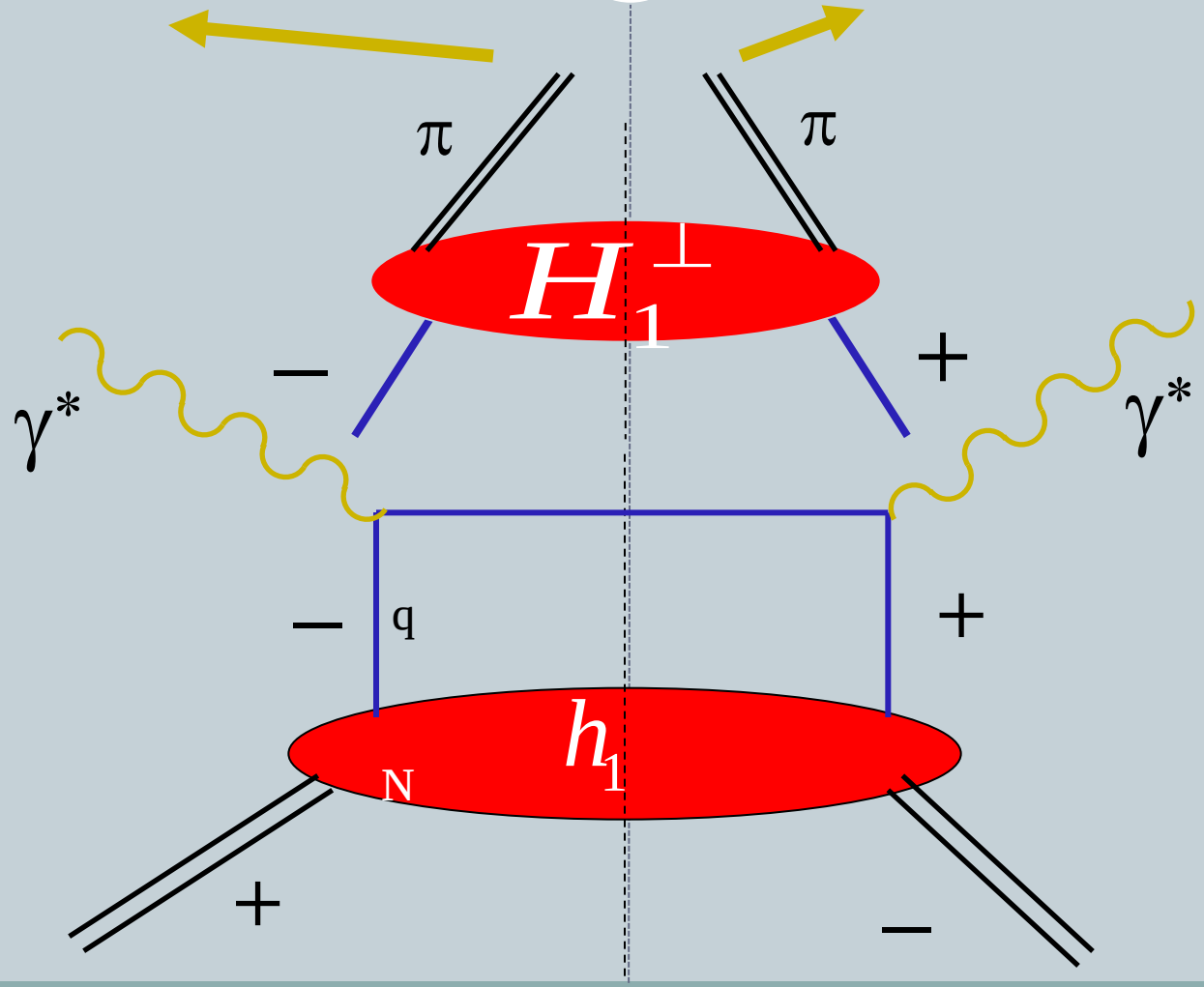
Only way to access tensor charge: $\langle |\sigma^{\mu\vartheta}| \rangle = \int dx (h_q(x) - h_{\bar{q}}(x)) = gT$

- **Tensor charge g_T can come from lattice and experiment**
  - Parton distributions on the light-cone → compare moments
- Allows first order calculations connection to experiment
- Other quantities from lattice: Quark orbital momentum etc



Chiral odd Fragmentation Functions

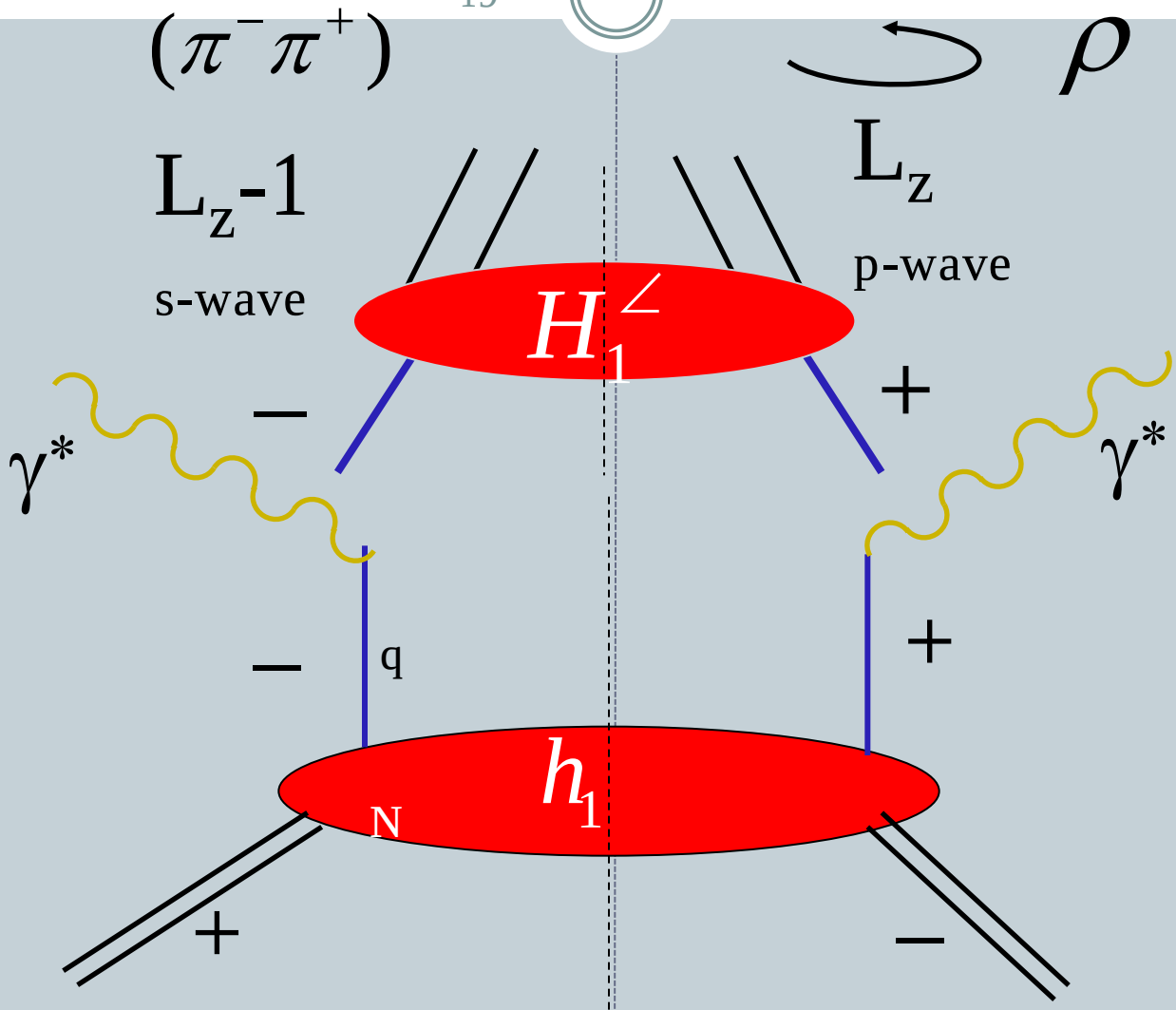
Collins effect



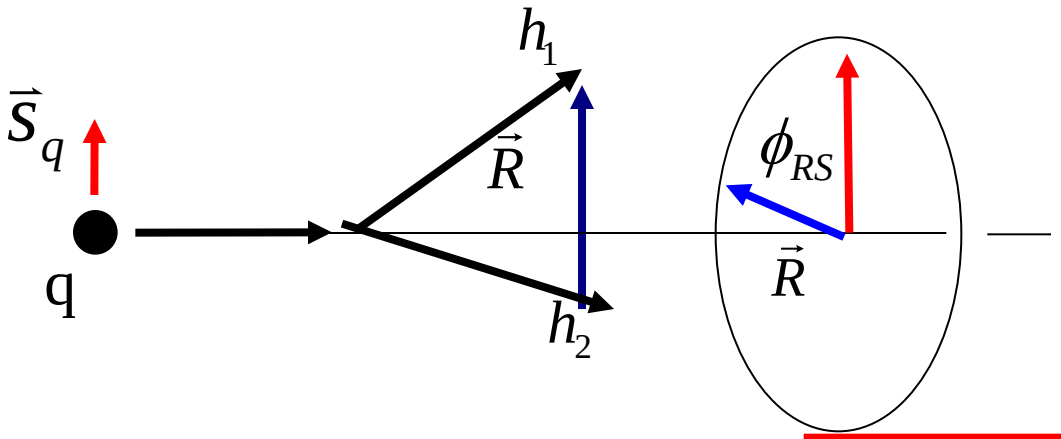
$H_1^\perp$: **Collins FF**

Chiral odd FFs

Interference Fragmentation Function



Quark Polarimetry with Interference FF in Quark Fragmentation



$\vec{k}$	: quark momentum
$\vec{s}_q$	:quark spin
$\vec{R}$	: momentum difference $\vec{p}_{h1} - \vec{p}_{h2}$
$\vec{R}_T$	transverse hadron momentum difference
z_{pair}	$= E_{pair}/E_q$
$=2E_{pair}/\sqrt{s}$	: relative hadron pair momentum
m	: hadron pair invariant mass

Interference Fragmentation Function:
Fragmentation of a transversely polarized quark *q* into two spin-less hadron *h1, h2* carries an azimuthal dependence:

$$\propto \left(\vec{k} \times \overrightarrow{R_T}\right) \cdot \overrightarrow{s_q}$$
$$\propto \sin \phi_{RS}$$

Transversity from di-Hadron SSA

p+p c.m.s. = lab frame

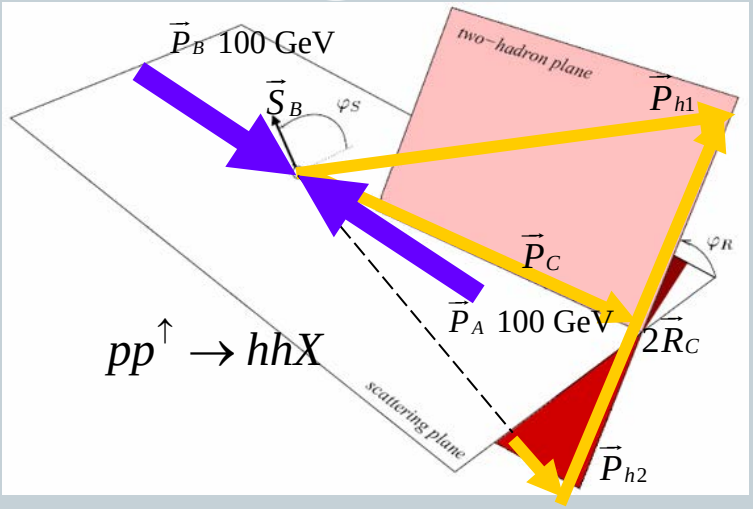
$\vec{P}_A, \vec{P}_B$: momenta of protons

$\vec{P}_{h1}, \vec{P}_{h2}$: momenta of hadrons

$\vec{P}_C = \vec{P}_{h1} + \vec{P}_{h2}$

$\vec{R}_C = (\vec{P}_{h1} - \vec{P}_{h2})/2$

$\vec{S}_B$: proton spin orientation



ϕ_R : from scattering plane to hadron plane

ϕ_S : from polarization vector to scattering plane

$$d\sigma_{UT} = 2\,|\mathbf{P}_{C\perp}| \sum_{a,b,c,d} \frac{|\mathbf{R}_C|}{M_C}\,|\mathbf{S}_{BT}|\,\sin(\phi_{S_B} - \phi_{R_C}) \int \frac{dx_a dx_b}{16\pi z_c}\, f_1^a(x_a)\, h_1^b(x_b)\, \frac{d\Delta\hat{\sigma}_{ab^{\uparrow}\to c^{\uparrow}d}}{d\hat{t}}\, H_{1,ot}^{\sphericalangle c}(\bar{z}_c, M_C^2)$$

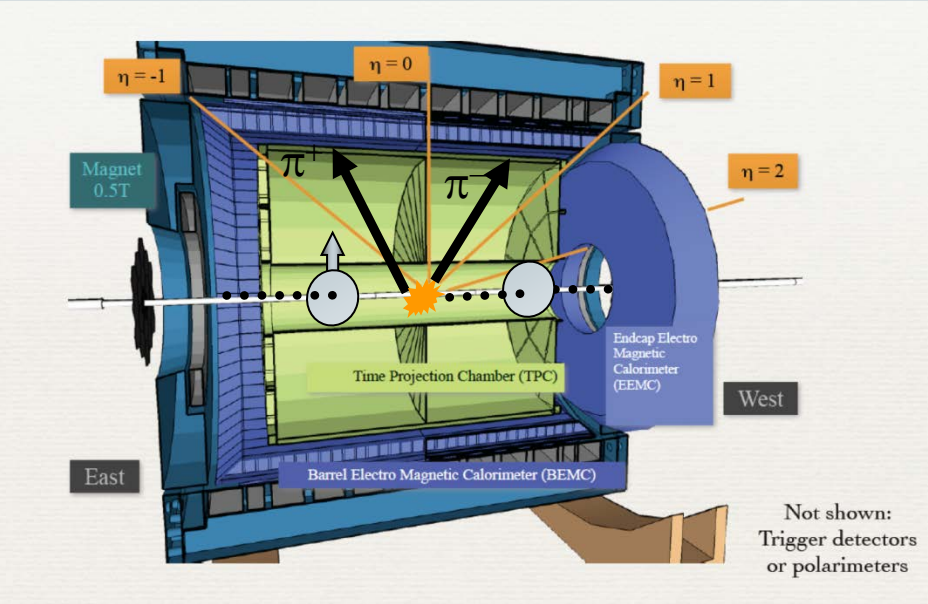
Unpolarized quark distribution
Known from DIS

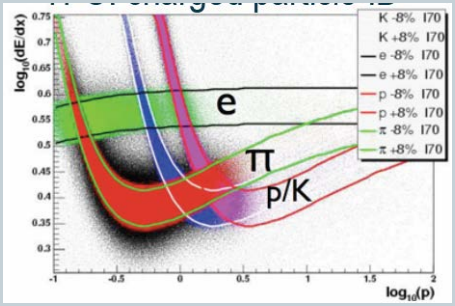
Transversity
to be extracted

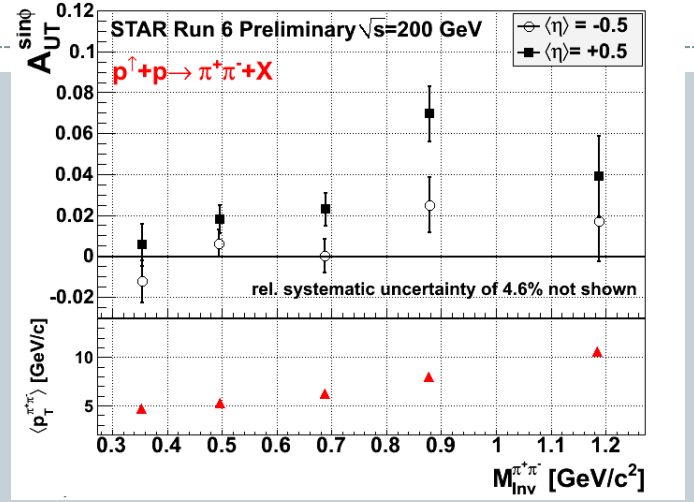
Hard scattering cross section
from pQCD

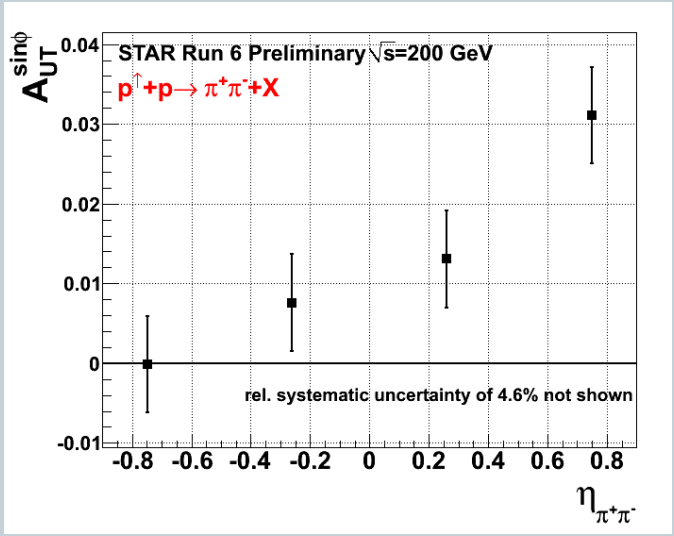
IFF + Di-hadron FF
measured in e+e at Belle-

NEW: STAR shows significant Signal!





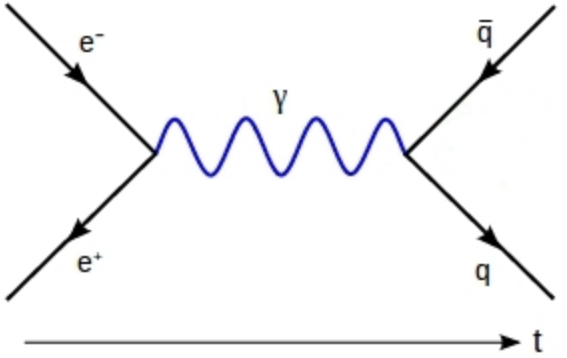




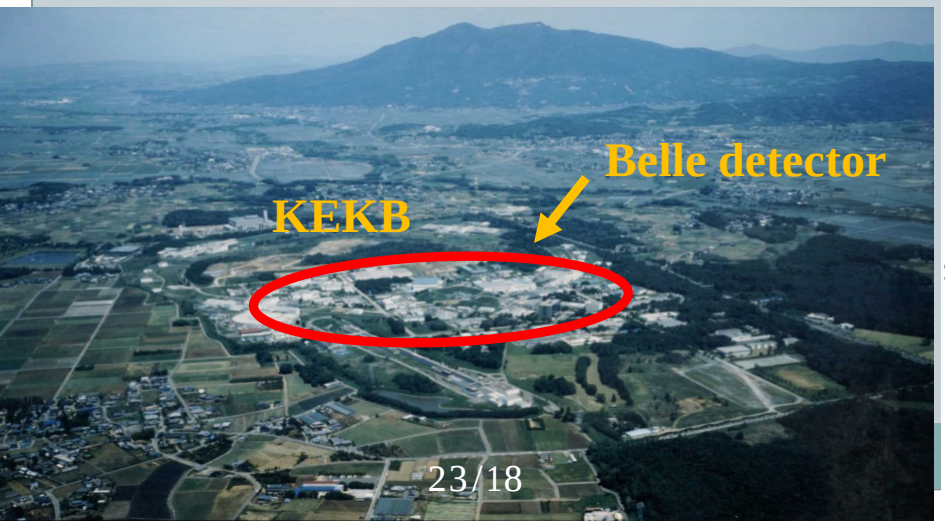
- First significant signal of transversity in polarized proton collisions

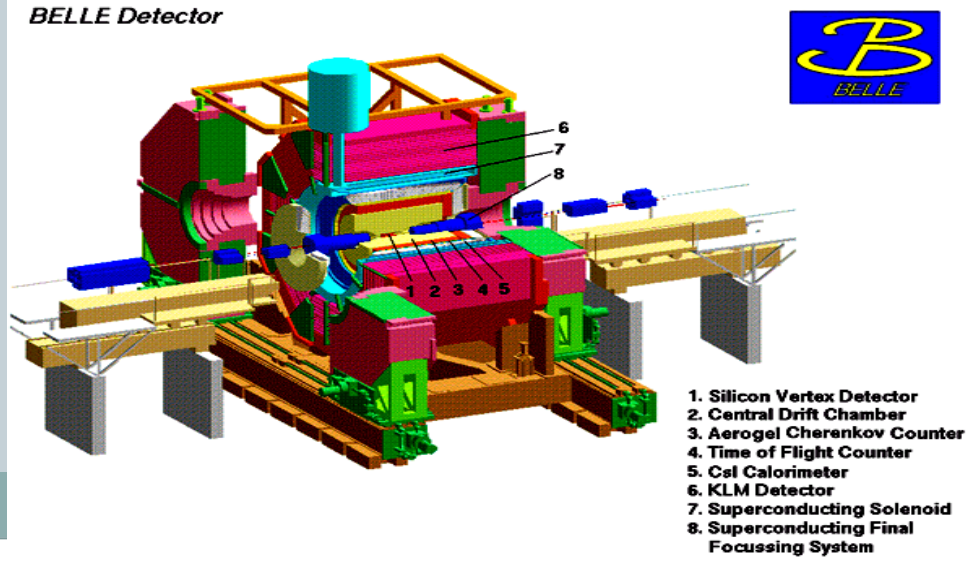
$$A_{UT} \propto h_1 \cdot H^{<}_1$$

Measurements of Fragmentation Functions in e+e- at Belle

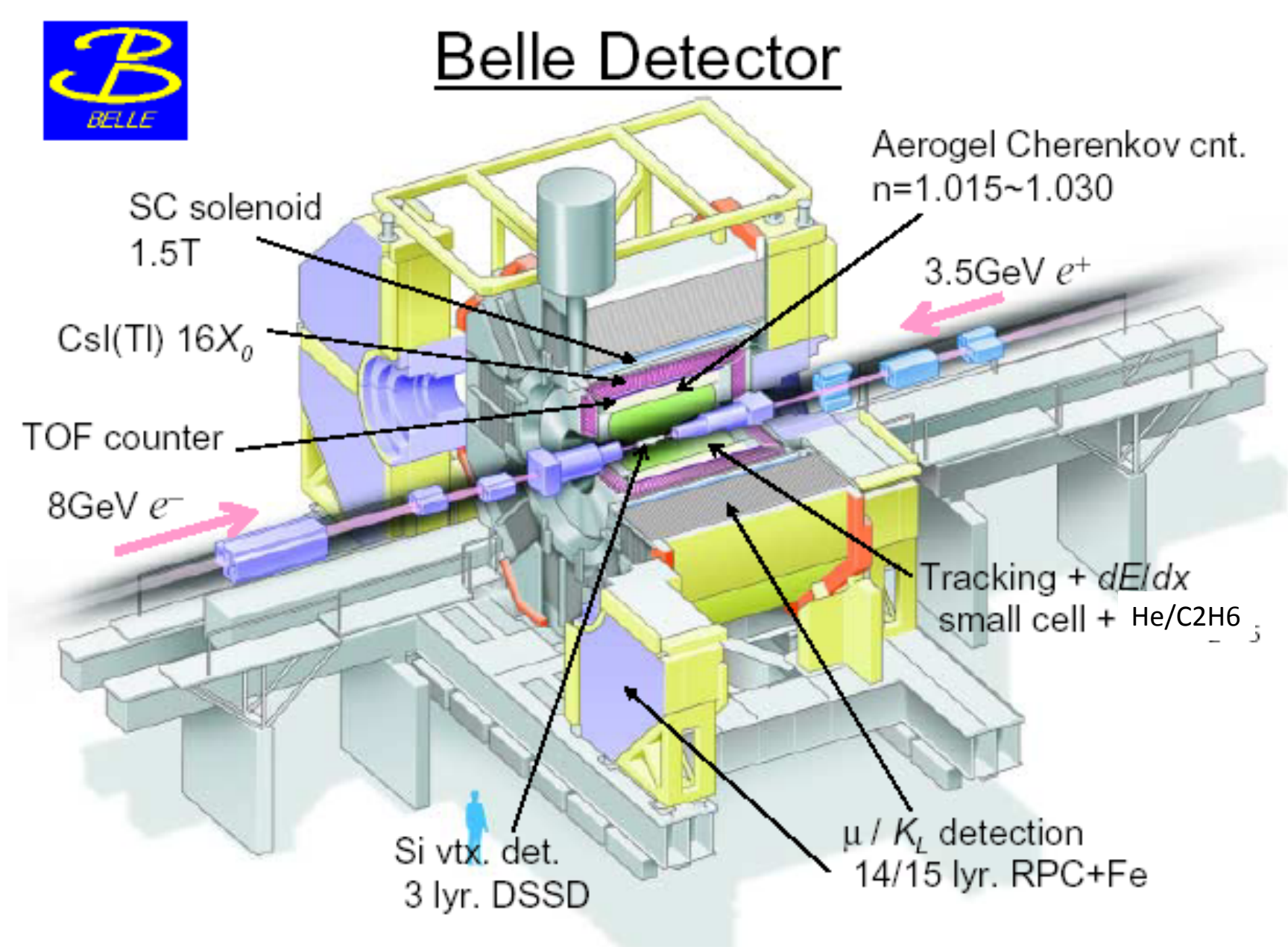


- KEK-B: asymmetric e^+ (3.5 GeV) e^- (8 GeV) collider:
  - **$\sqrt{s}$ = 10.58 GeV,** $e^+e^- \rightarrow \Upsilon(4S) \rightarrow B\bar{B}$
  - $\sqrt{s}$ = 10.52 GeV, e+e- → qqbar (u,d,s,c) 'continuum'
- ideal detector for high precision measurements:
  - tracking acceptance θ [17 °;150°]: Azimuthally symmetric
  - particle identification (PID): dE/dx, Cherenkov, ToF, EMcal, MuID
- Available data:
  - ~1.8 *10^9 events at 10.58 GeV,
  - ~220 *10^6 events at 10.52 GeV





Belle Detector



Large acceptance, good tracking and particle identification!

dE/dx (CDC)

Δ dE/dX ~ 5 %

TOF (only Barrel)

Δ T ~ 100 ps (r = 125cm)

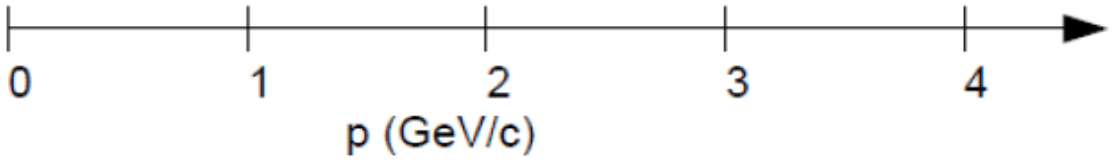
Barrel ACC

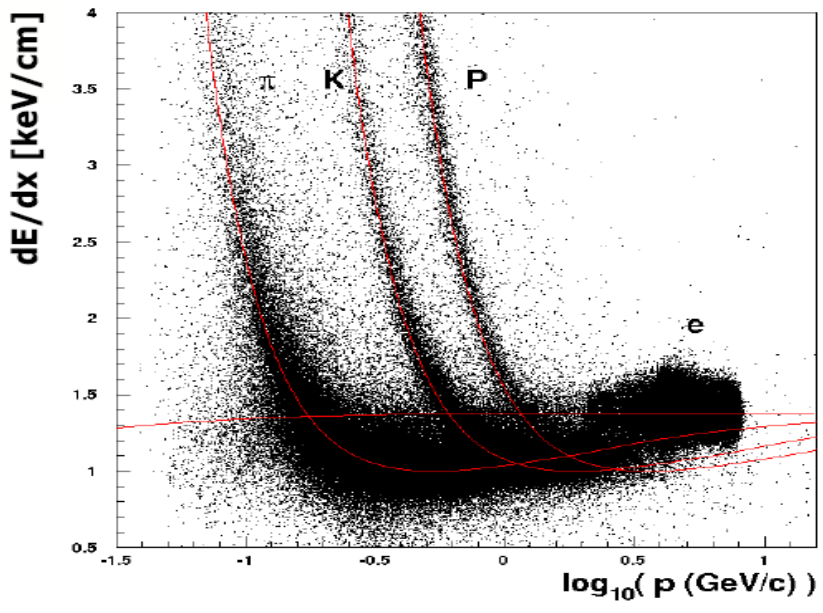
n = 1.010 ~ 1.028

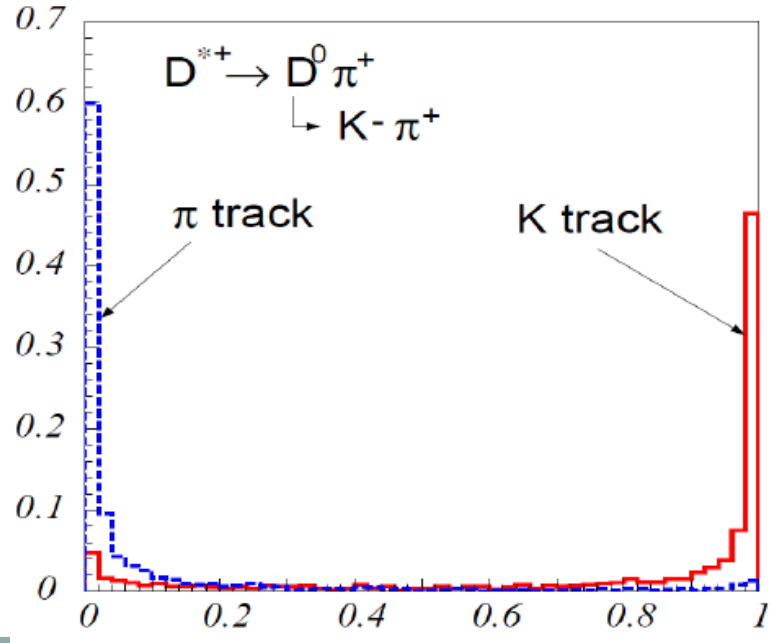
Endcap ACC

n = 1.030

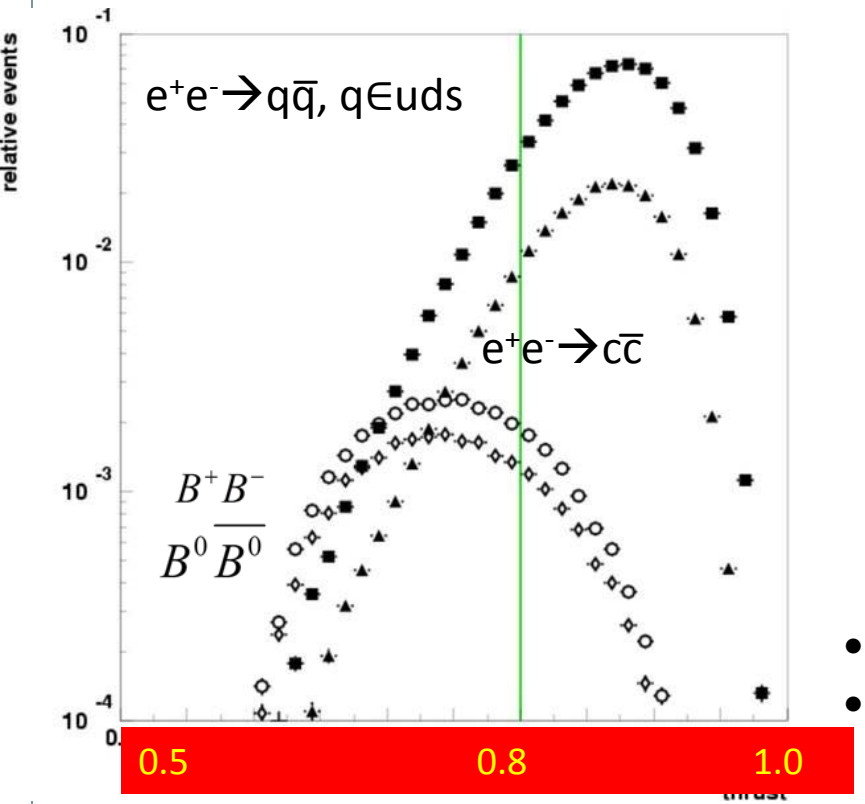
(only flavor tagging)



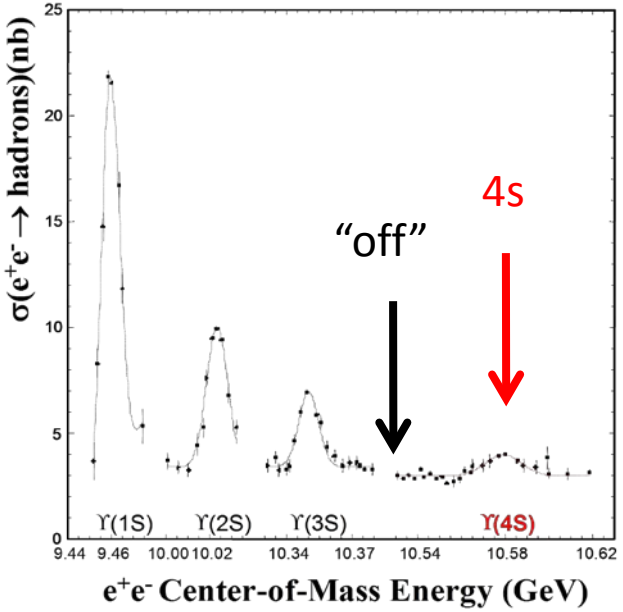




Measuring Light Quark Fragmentation Functions on the Υ(4S) Resonance

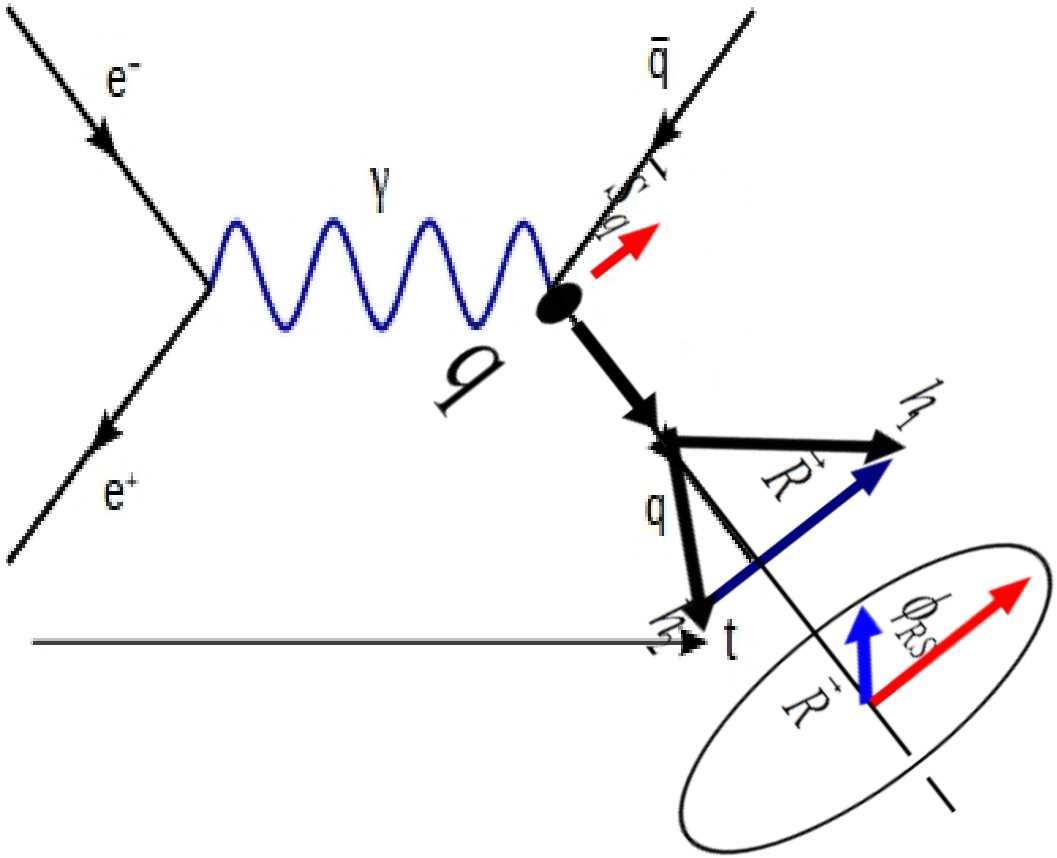


$$Thrust: T = \frac{\sum_i |p_i \cdot \hat{n}|}{\sum_i |p_i|}$$

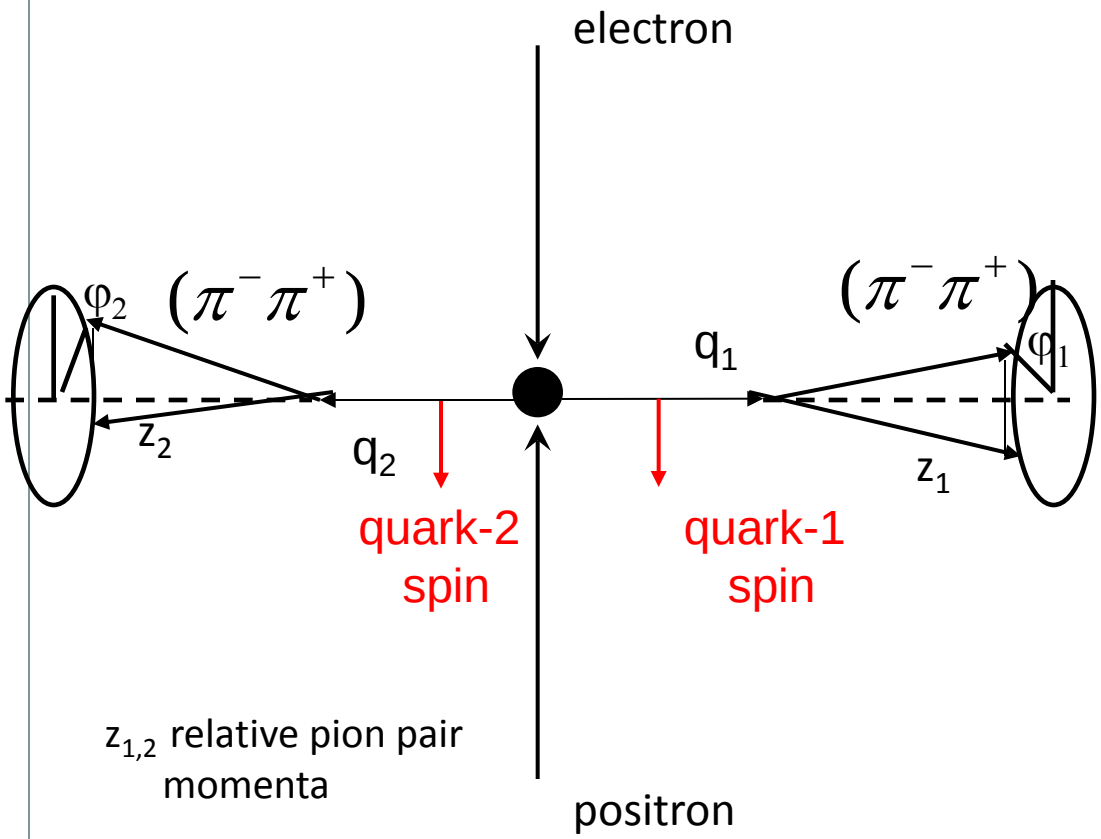


- small B contribution (<1%) in high thrust sample
- >75% of X-section continuum under Υ (4S) resonance
- ~100 fb^{-1} ➔ ~1000 fb^{-1}

How to Measure Spin Dependent Fragmentation Functions in unpolarized $e^+ e^-$



Measuring transverse spin dependent di-Hadron Correlations In unpolarized e^+e^- Annihilation into Quarks



Interference effect in e^+e^- quark fragmentation will lead to azimuthal asymmetries in di-hadron correlation measurements!

Experimental requirements:

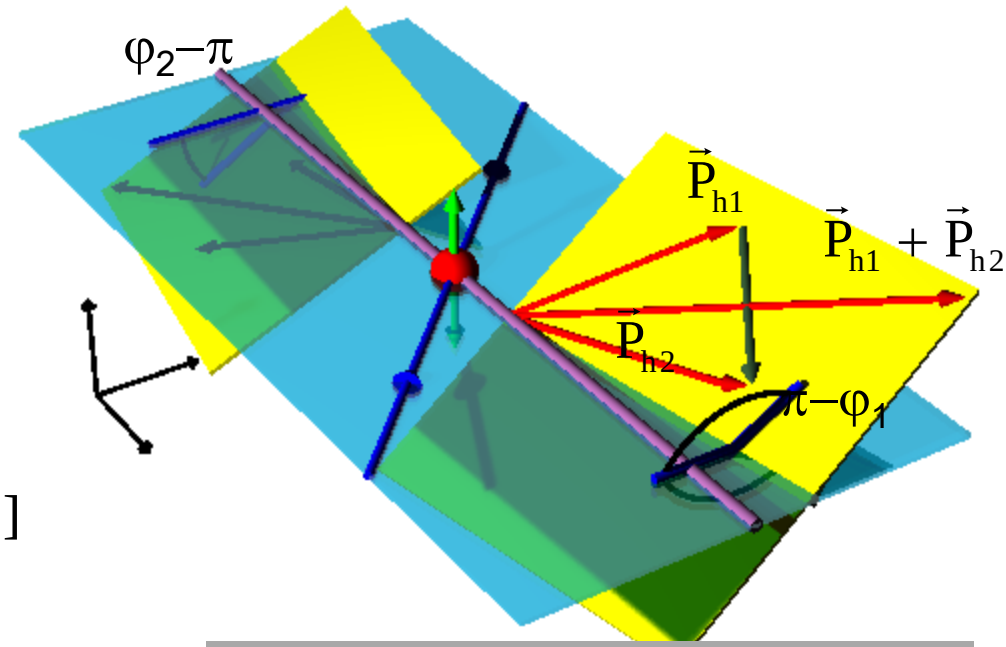
- Small asymmetries ➔ very large data sample!
- Good particle ID to high momenta.
- Hermetic detector

$$A \propto H_1^{\sphericalangle}(z_1, m_1)\overline{H}_1^{\sphericalangle}(z_2, m_2)\cos(\varphi_1 + \varphi_2)$$

Interference Fragmentation Function from di-Hadron Pair Correlations

- $e^+e^- \rightarrow (\pi^+\pi^-)_{jet1}(\pi^+\pi^-)_{jet2}X$
- Find pion pairs in opposite hemispheres
- Observe angles $\varphi_1+\varphi_2$ between the event-plane (beam, jet-axis) and the two two-pion planes.
- Theoretical guidance by papers of Boer,Jakob,Radici[PRD 67,(2003)] and Artru,Collins[ZPhysC69(1996)]
- Early work by Collins, Heppelmann, Ladinsky [NPB420(1994)]

$$A \propto H_1^{\angle}(z_1, m_1)\overline{H}_1^{\angle}(z_2, m_2)\cos(\varphi_1 + \varphi_2)$$



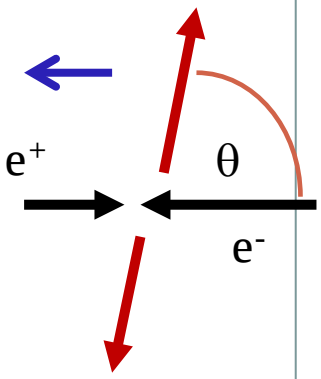
Model predictions by:

- Jaffe et al. [PRL **80,**(1998)]
- Radici et al. [PR**D 65,**(2002)]

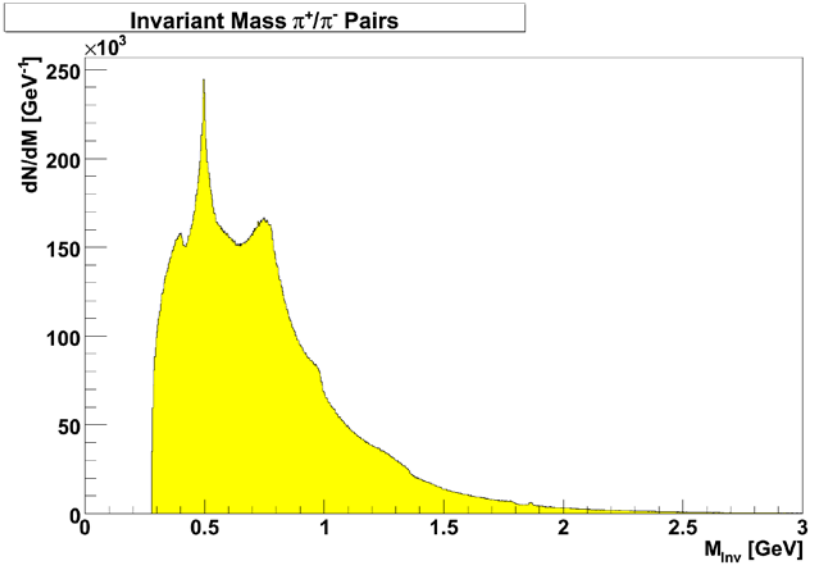
Transverse Spin Dependent FFs: Cuts and Binning

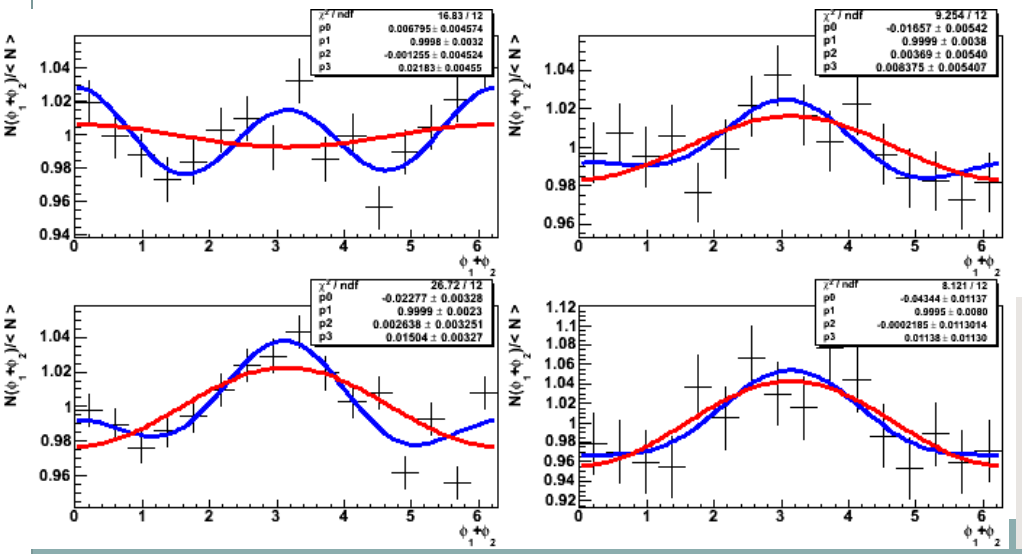
- Full off-resonance and on-resonance data (7-55): ~73 fb^{-1} + 588 fb^{-1}
- Visible energy >7GeV, exclusion of $\tau^- \rightarrow \pi^-\pi^+\pi^-\nu_\tau$
- PID: Purities in for di-pion pairs > 90%
- Same Hemisphere cut within pair ($\pi^+\pi^-$), opposite hemisphere between pairs
- All 4 hadrons in barrel region: $-0.6 < \cos(\theta) < 0.9$
- Thrust axis in central area: cosine of thrust axis around beam <0.75
- Thrust > 0.8 to remove B-events → < 1% B events in sample
- $z_{had1,had2} > 0.1$
- $z_1 = z_{had1} + z_{had2}$ and z_2 binning
- $m_{\pi\pi 1}$ and $m_{\pi\pi 2}$ binning
- $m_{\pi\pi 1}, z_1$ binning

T-spin projection: $\mathrm{Sin}(\theta)^2/1+\cos(\theta)^2$



Asymmetry extraction





- Build normalized yields:

$$\frac{N(\phi_1+\phi_2)}{\langle N\rangle},$$

- Fit with:

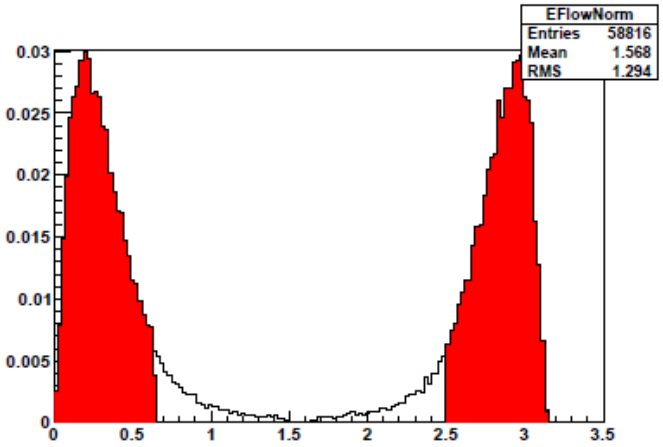
$$a_{12}\cos(\phi_1+\phi_2)+b_{12}$$

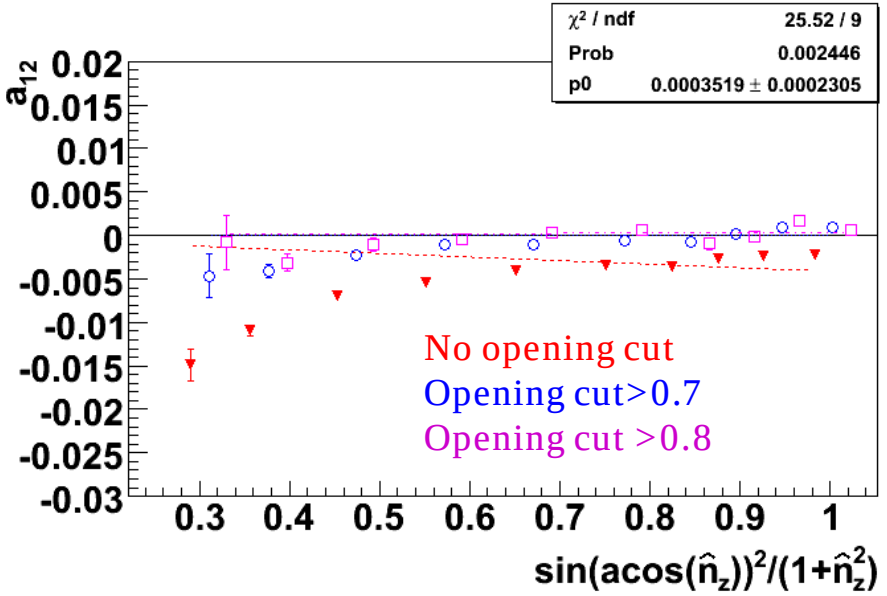
or

$$a_{12}\cos(\phi_1+\phi_2)+b_{12}+$$
$$c_{12}\cos 2(\phi_1+\phi_2)+d_{12}\sin(\phi_1+\phi_2)$$

Amplitude a_{12} directly measures (IFF) x (-IFF) (no double ratios)

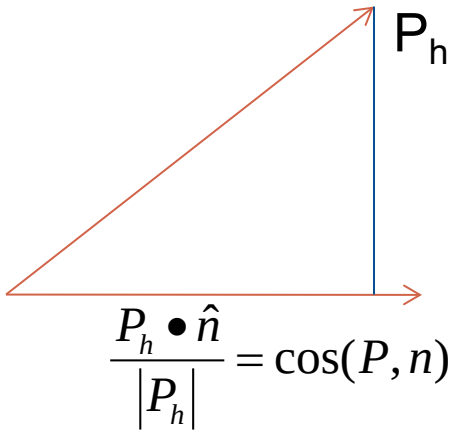
Zero tests: MC





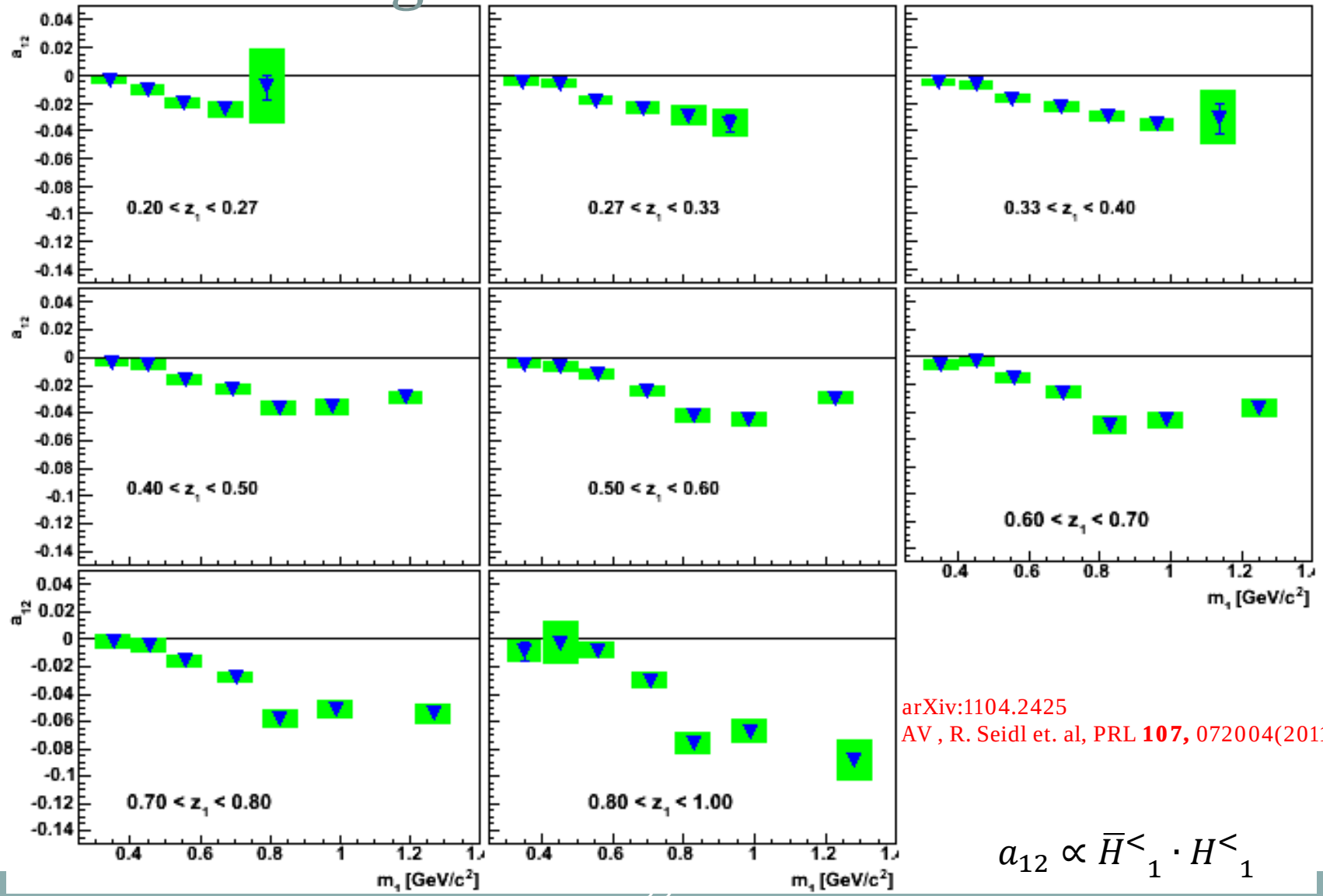
Energy flow with opening cut of 0.8

- A small asymmetry seen due to acceptance effect
- Mostly appearing at boundary of acceptance
- Opening cut in CMS of 0.8 (~37 degrees) reduces acceptance effect to the sub-per-mille level



$$\frac{P_h \bullet \hat{n}}{|P_h|} = \cos(P, n)$$

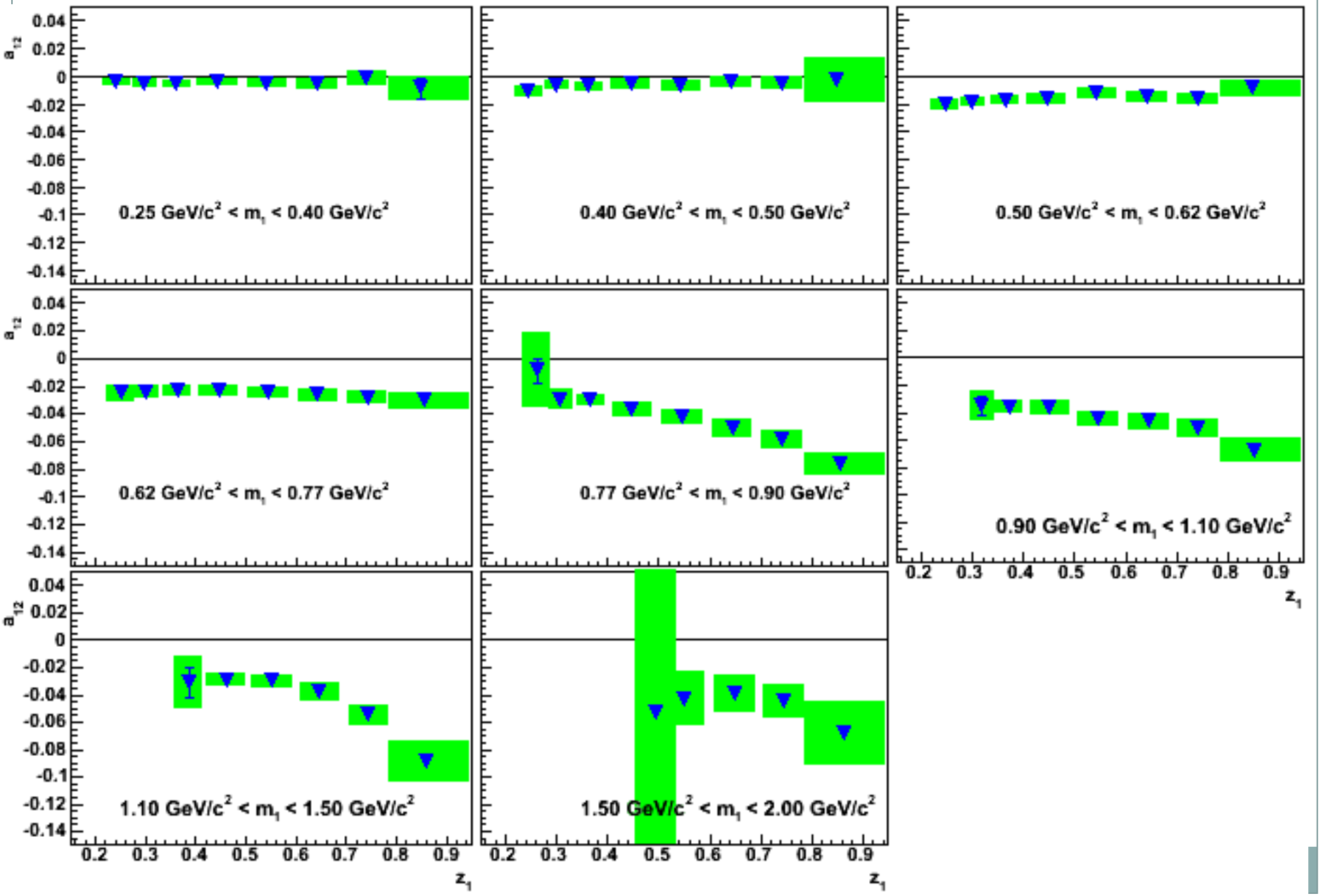
First measurement of Interference Fragmentation Function



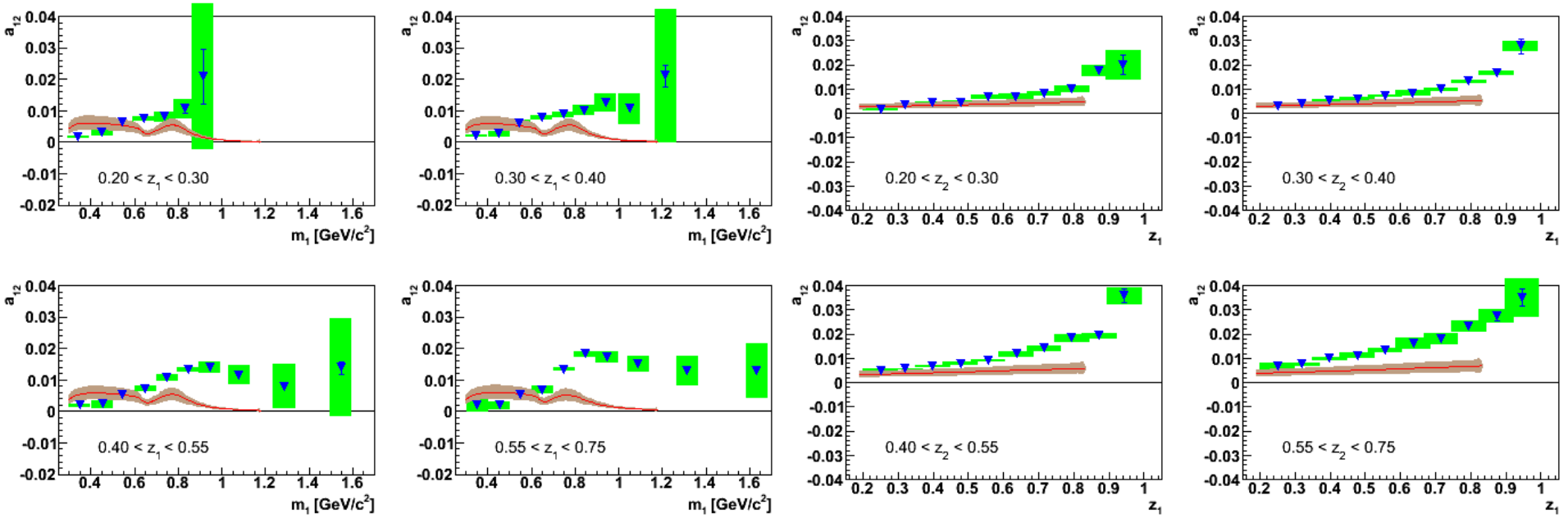
arXiv:1104.2425
AV , R. Seidl et. al, PRL **107,** 072004(2011)

$$a_{12} \propto \bar{H}^{<}{}_1 \cdot H^{<}{}_1$$

$(m_1 x\ z_1)$ Binning



Comparison to theory predictions



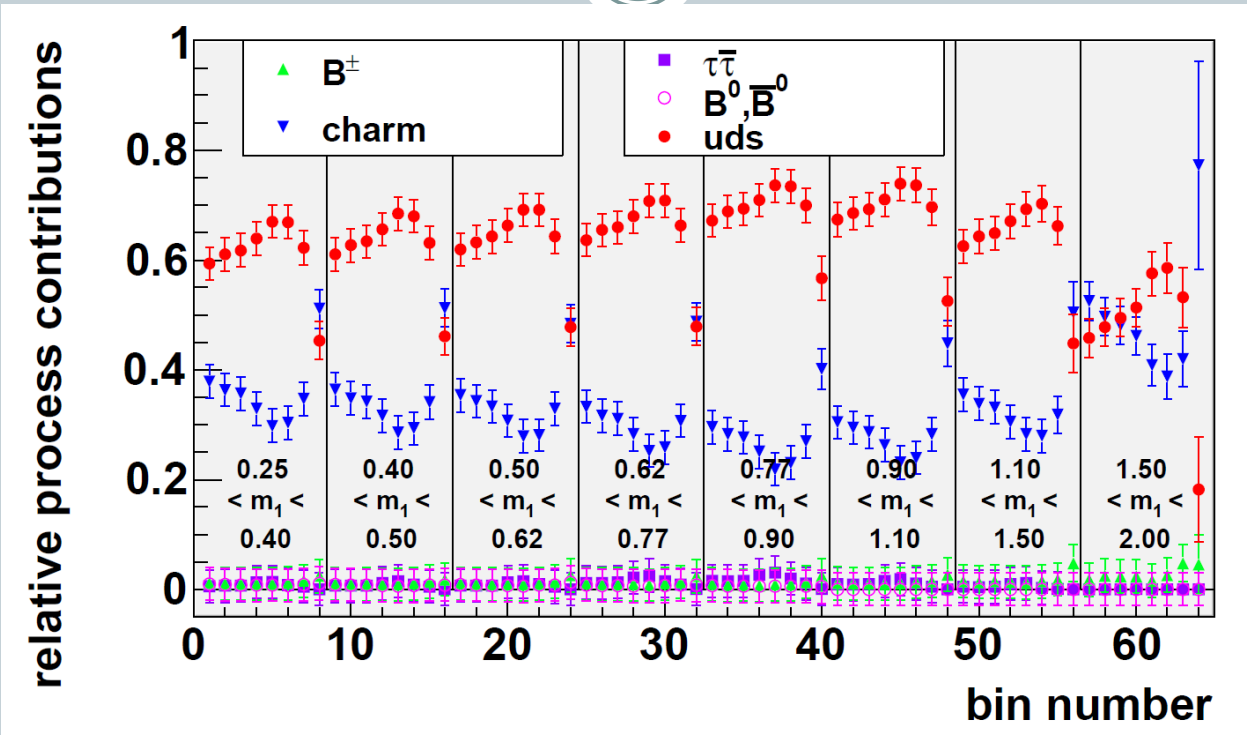
Red line: theory prediction + uncertainties

Blue points: data

- Mass dependence : Magnitude at low masses comparable, high masses significantly larger (some contribution possibly from charm)
- Z dependence : Rising behavior steeper

Subprocess contributions (MC)

8x8 m_1 m_2 binning



tau contribution (only significant at high z)

charged B(<5%, mostly at higher mass)

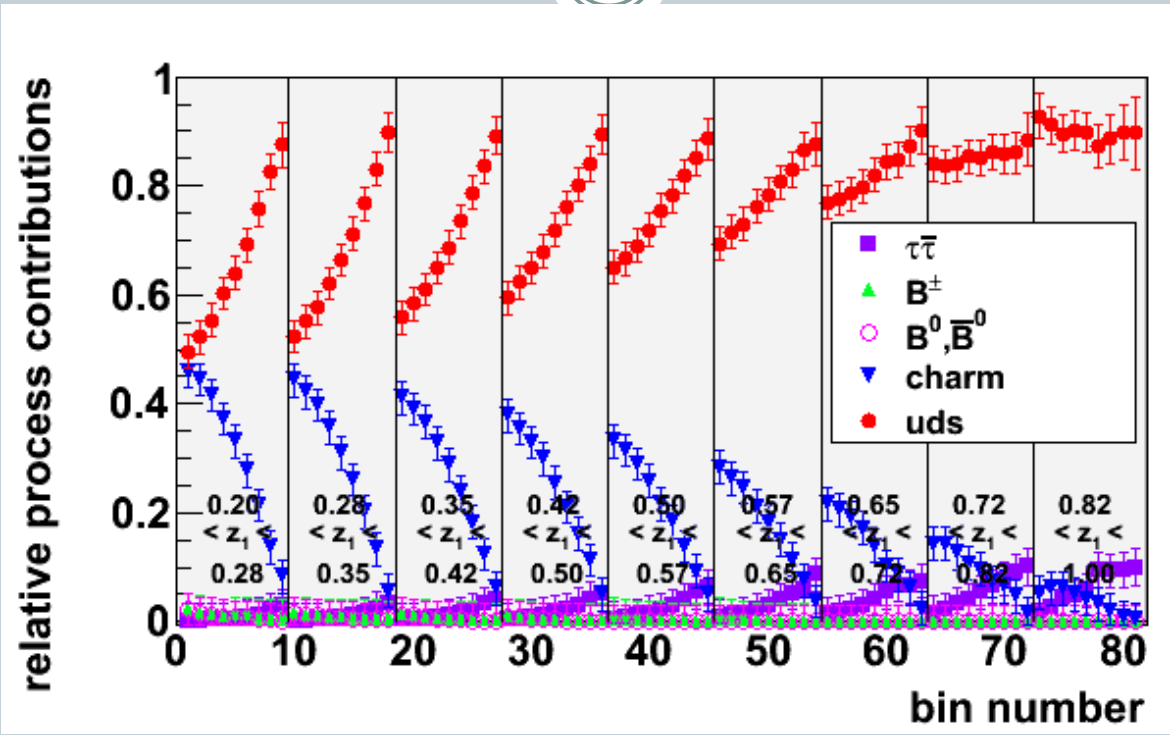
Neutral B (<2%)

charm(20-60%, mostly at lower z)

uds (main contribution)

Subprocess contributions (MC)

9x9 z_1 z_2 binning



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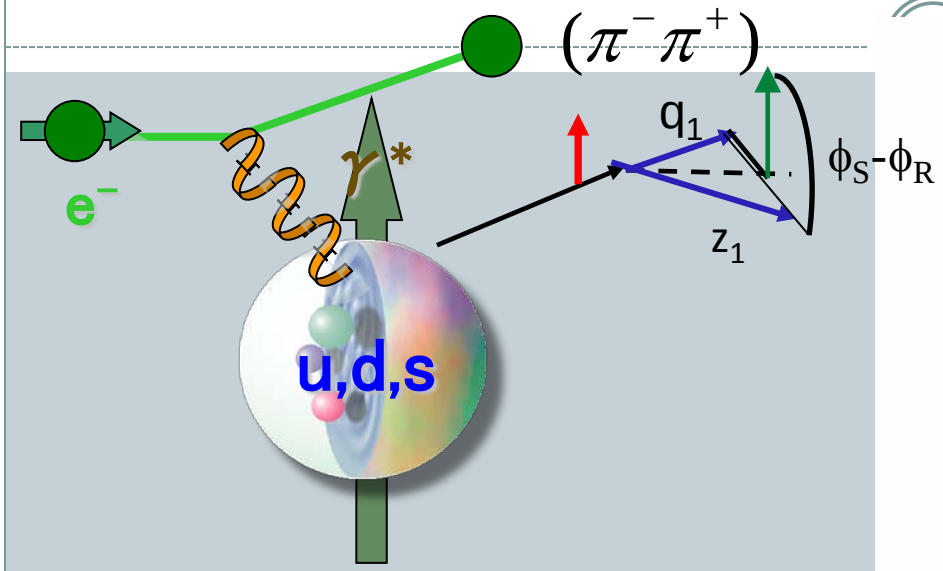
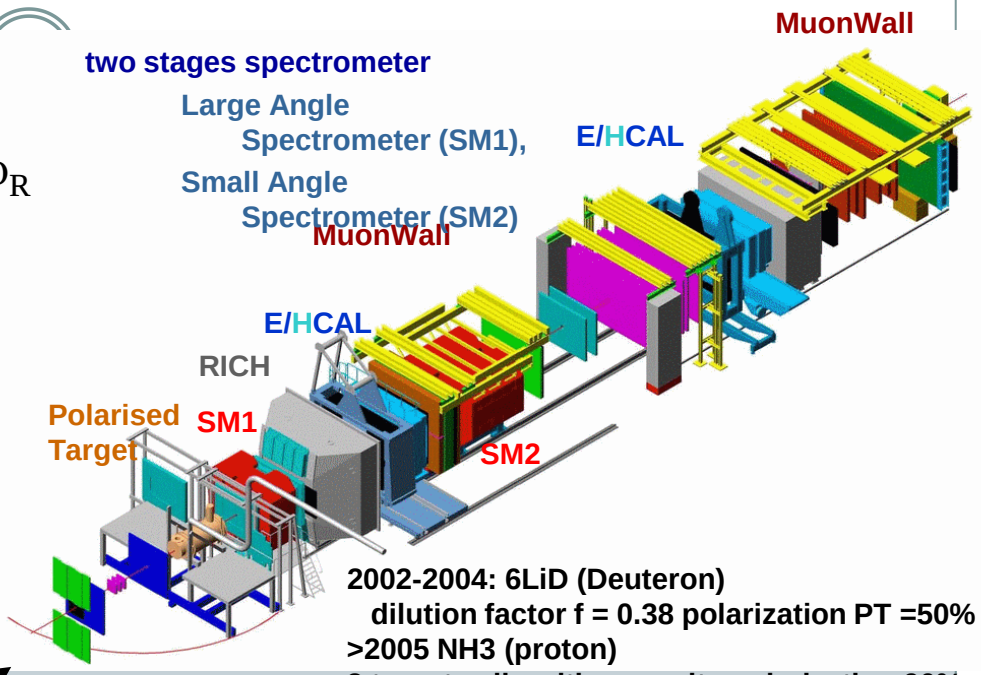
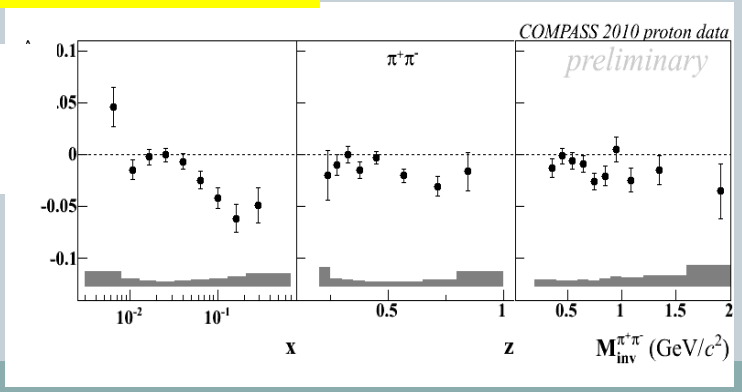
COMPASS 2004 Setup





$$\frac{\sigma^{\uparrow}-\sigma^{\downarrow}}{\sigma^{\uparrow}+\sigma^{\downarrow}}(\phi_S-\phi_R)=A_{UT}\sin(\phi_S-\phi_R)$$

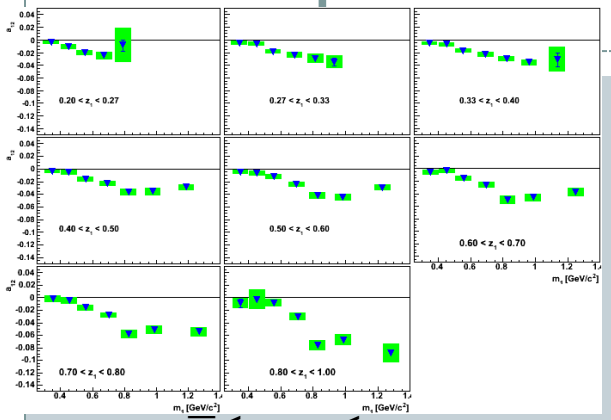
$$A_{UT} \propto h_1 \cdot H^{<}_1$$



2002-2004: 6LiD (Deuteron)
dilution factor f = 0.38 polarization PT =50%
>2005 NH3 (proton)
3 target cells with opposite polarization,90% polarization, 16% dilution

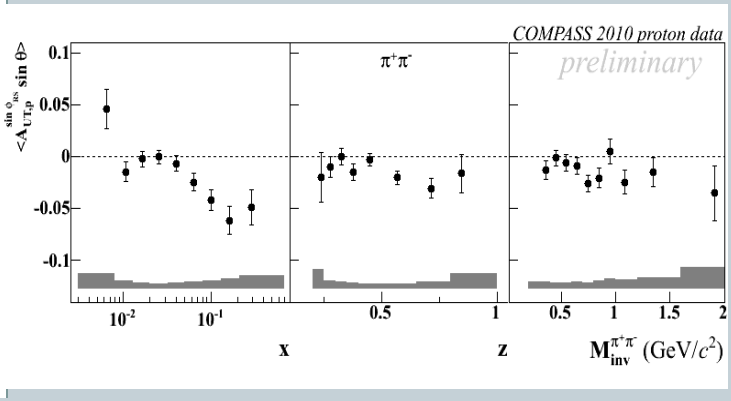
- high energy beam
- Large angular acceptance
- Broad kinematical range

Measurement at Belle leads to first point by point extraction of Transversity



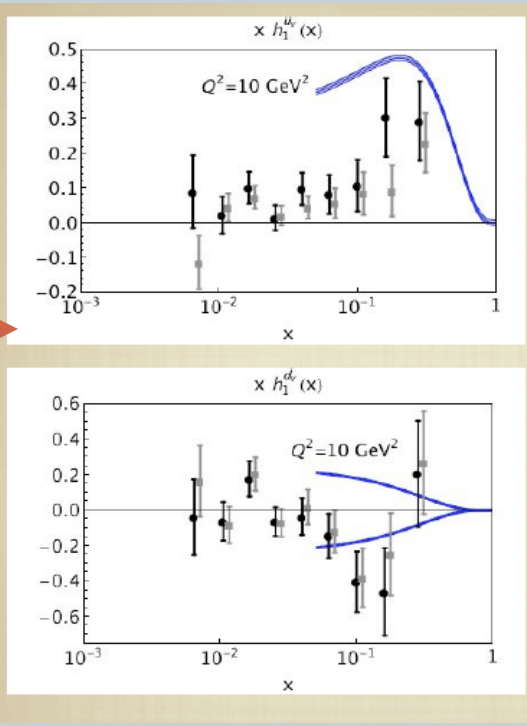
$$a_{12} \propto \bar{H}^{<}_{1} \cdot H^{<}_{1}$$

+



$$A_{UT} \propto h_1 \cdot H^{<}_{1}$$

M. Radici at FF workshop, RIKEN, 11/2012
See also: Courtoy: Phys. Rev. Lett. 107:012001,2011



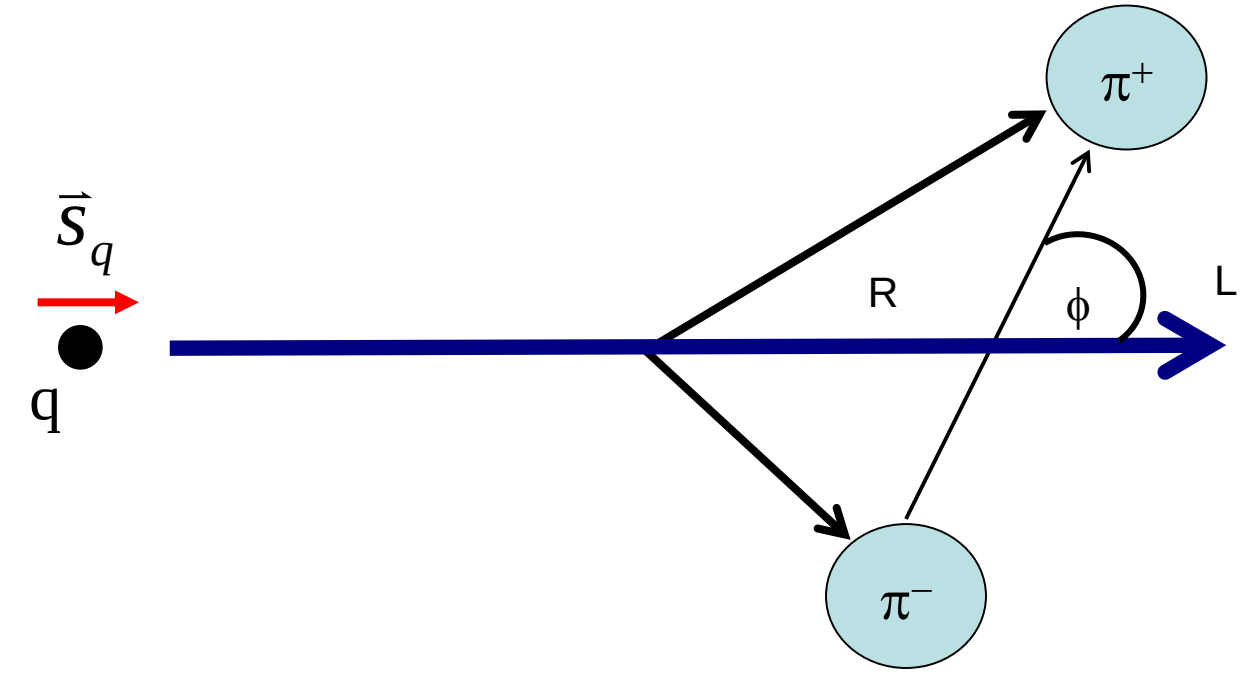
Is Soffer Bound violated?
h(x)<|f(x)+g(x)|/2

Future Plans at Star/Belle:

Better sensitivity to d transversity
From $\pi^0/\pi^{+/-}$ combinations

Increase x range

Jet Handedness



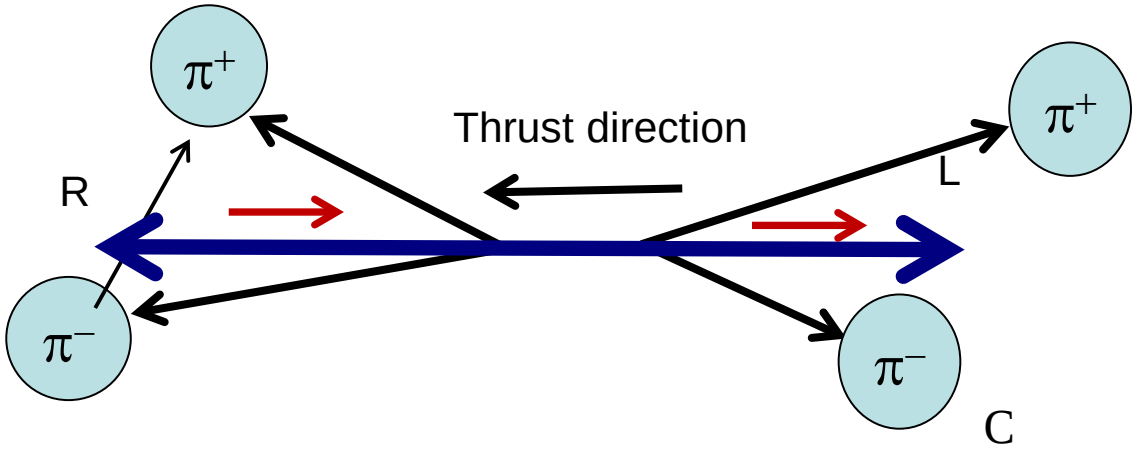
Handedness: $\frac{(\overrightarrow{k_+} \times \overrightarrow{k_-}) \cdot \vec{t}}{|k_+||k_-|}$ ⇨ L/R

$\overset{?}{=} \sin\Phi > 0$

Jet handedness: $\frac{N_R - N_L}{N_R + N_L}$

Handedness Correlations

- Handedness Correlations expected to be zero in factorized approach
- Non-zero asymmetries predicted in factorized approach for azimuthal asymmetries sensitive to $G^{\perp}_1$
- Several suggestions how interactions with QCD vacuum can lead to non-zero asymmetries



Handedness: $\frac{(\overrightarrow{k_+} \times \overrightarrow{k_-}) \cdot \vec{t}}{|k_+||k_-|} >^{?} 0$ ⇨ L/R

Jet → $handedness: \frac{N_R - N_L}{N_R + N_L}$

C: $\frac{N_{RL} + N_{LR} - N_{RR} - N_{LL}}{N_{RL} + N_{LR} + N_{RR} + N_{LL}}$

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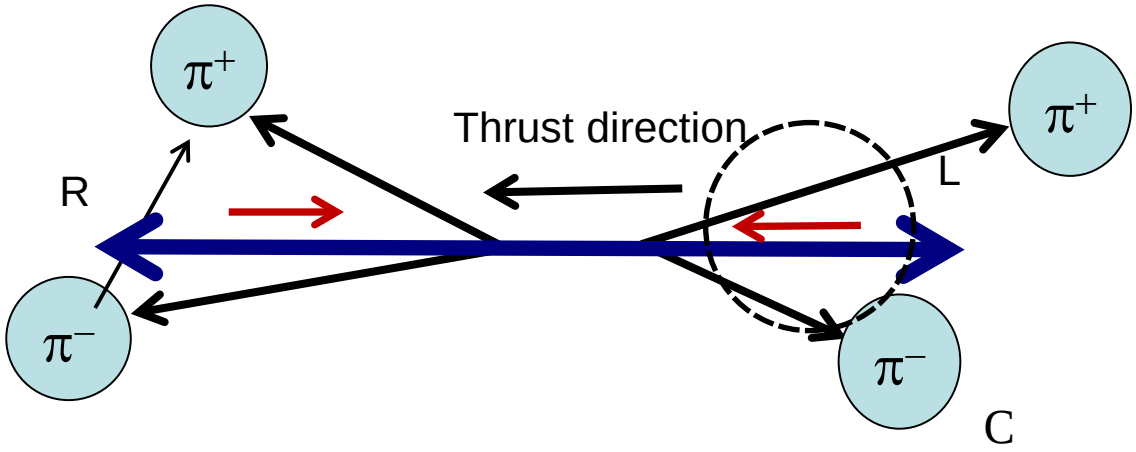

Handedness: $\dfrac{(\overrightarrow{k_+} \times \overrightarrow{k_-}) \cdot \vec{t}}{|\, k_+ \,||\, k_- \,|} >^{?} 0$ ⇨ L/R

Jet

$handedness: \dfrac{N_R - N_L}{N_R + N_L}$

C: $\dfrac{N_{RL} + N_{LR} - N_{RR} - N_{LL}}{N_{RL} + N_{LR} + N_{RR} + N_{LL}}$

Handedness Correlations

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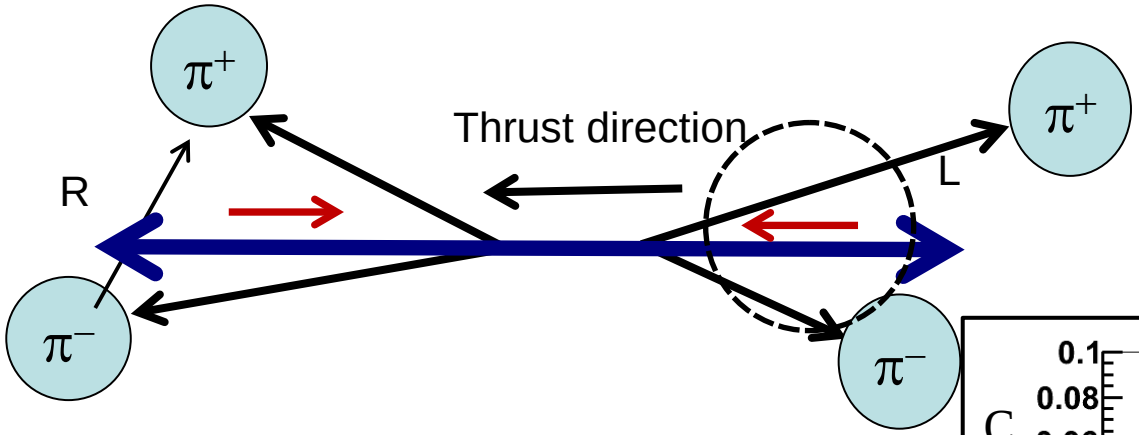
- Several suggestions how interactions with QCD vacuum can lead to non-zero asymmetries
- SLD: Upper bound from 90k hadronic Z events: 7%



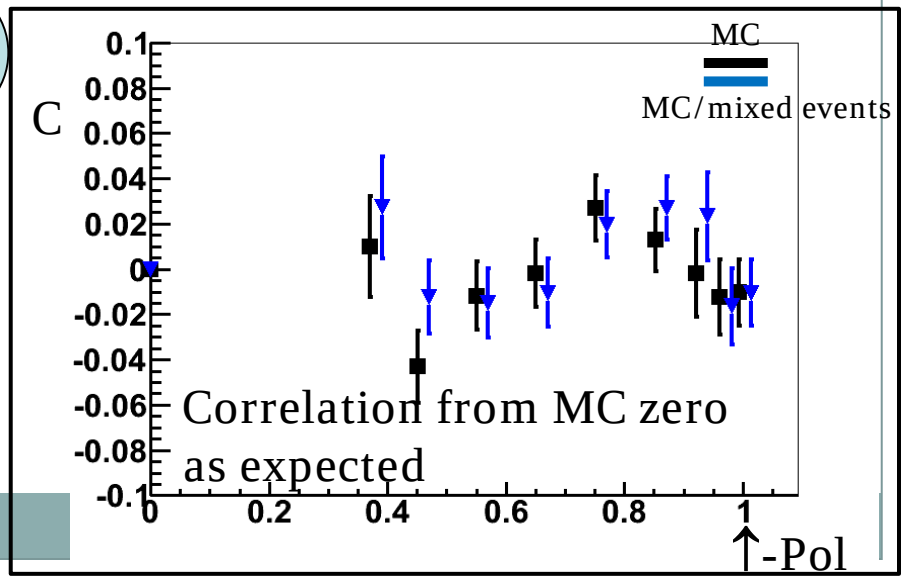
Handedness: $\frac{(\vec{k_+} \times \vec{k_-}) \cdot \vec{t}}{|k_+||k_-|} >^{?} 0$ ⇨ L/R

Jet

$\rightarrow$

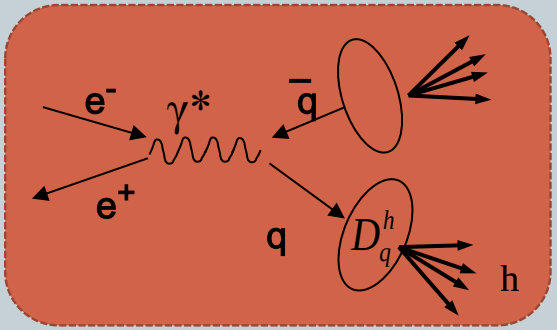
$handedness: \frac{N_R - N_L}{N_R + N_L}$

C: $\frac{N_{RL} + N_{LR} - N_{RR} - N_{LL}}{N_{RL} + N_{LR} + N_{RR} + N_{LL}}$

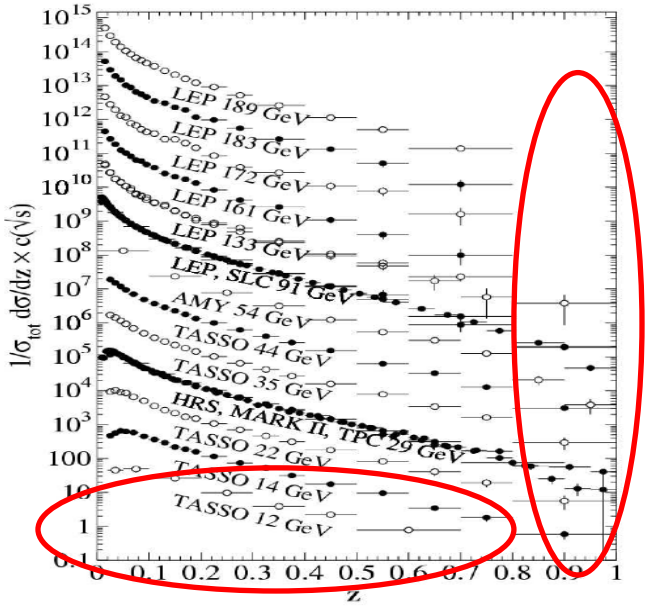


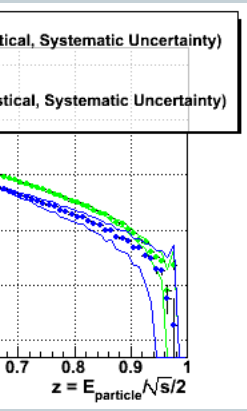
Unpolarized Fragmentation Functions

- Precise knowledge of upol. FFs necessary for virtually all SIDIS measurements



Lack of data at high z, lower CMS





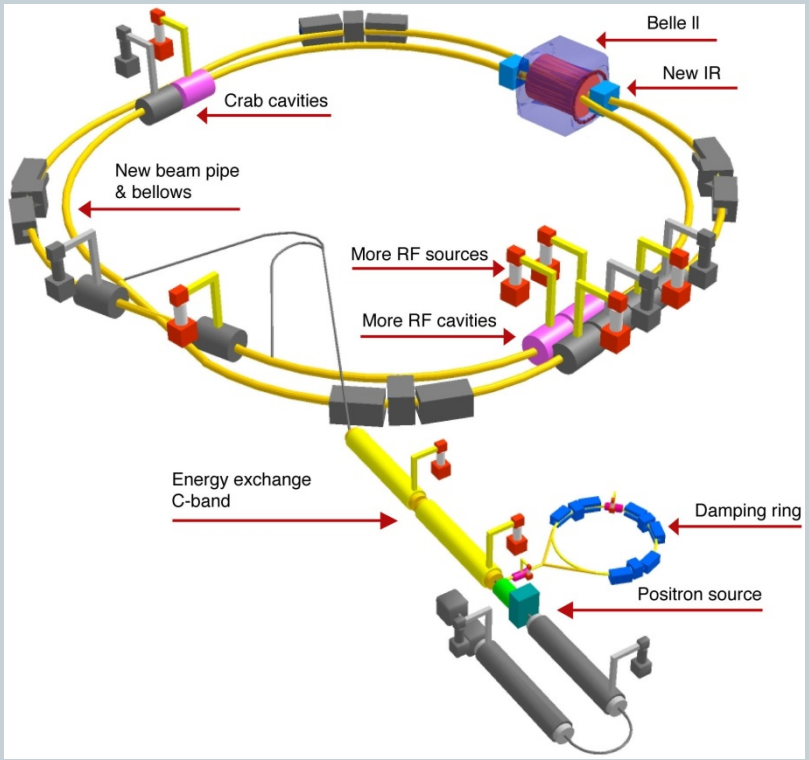
Submitted to PRL
arXiv:1301.6183

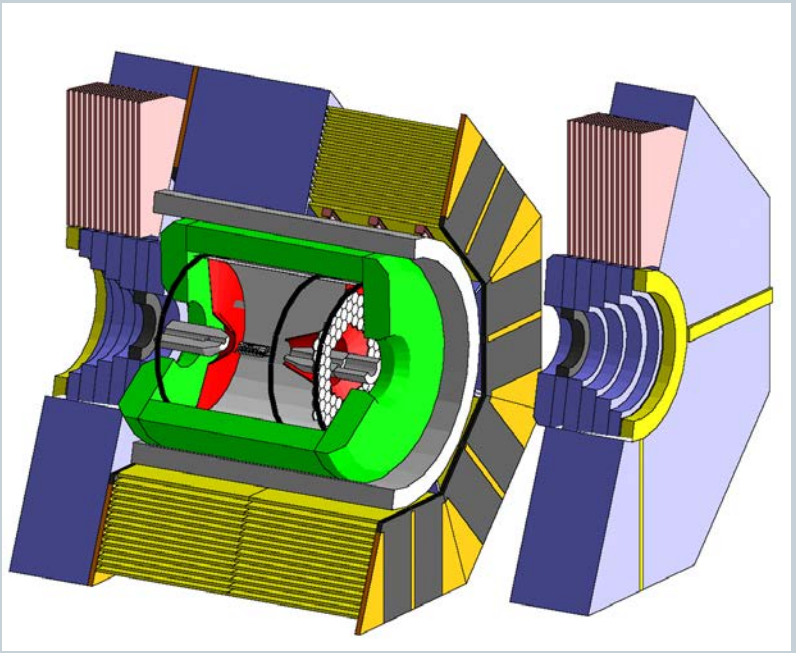
- π^0, η fragmentation function under way
- In particular important at RHIC

M. Leitgab (UIUC)

KEKB/Belle→SuperKEKB, upgrade (2010–2015)

- Aim: super-high luminosity ~10^{36} $cm^{-2}s^{-1}$ (~40x KEK/Belle)
  - Will allow p_T dependent extraction of fragmentation functions
- Upgrades of Accelerator (Microbeams + Higher Currents) and Detector Significant US contribution





http://belle2.kek.jp

Belle II Detector at SuperKEKB (L x 40)

and IU contributions to Barrel Particle ID

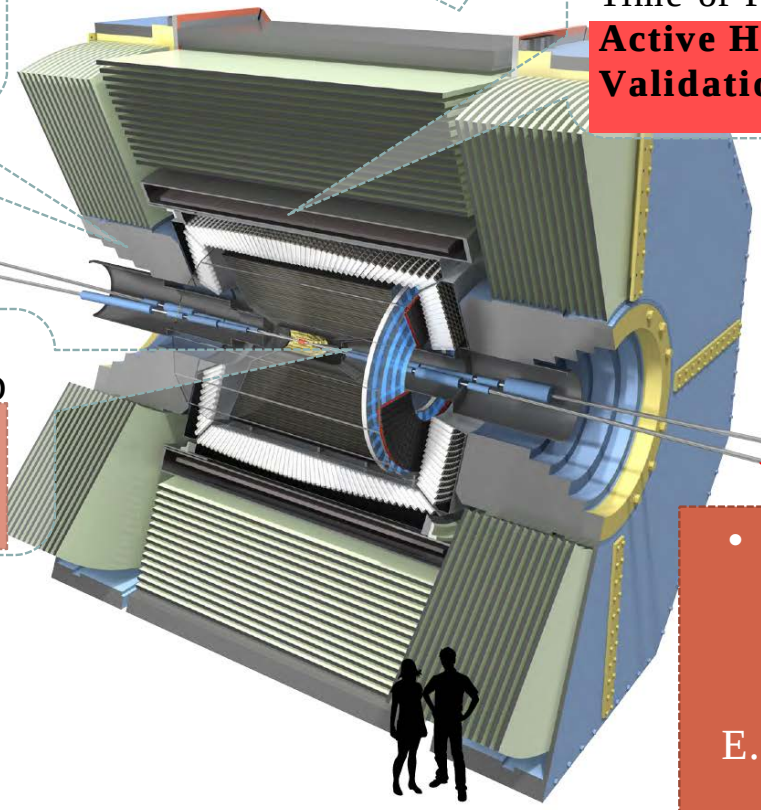
- Barrel PID instrumental for fragmentation function measurements

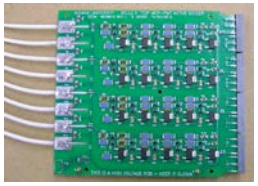
K_L and muon detector:
Resistive Plate Counter (barrel outer layers)
Scintillator + WLSF + MPPC (end-caps, inner 2 barrel layers)
RPC Front End Electronics, Concentrator boards for barrel and endcap scintillator layers

EM Calorimeter:
CsI(Tl), waveform sampling (barrel)
Pure CsI + waveform sampling (end-caps)

Particle Identification
Time-of-Propagation counter (barrel)
Active HV Divider board for MCP-PMT
Validation of FPGA code of iTOP

e- (7GeV)



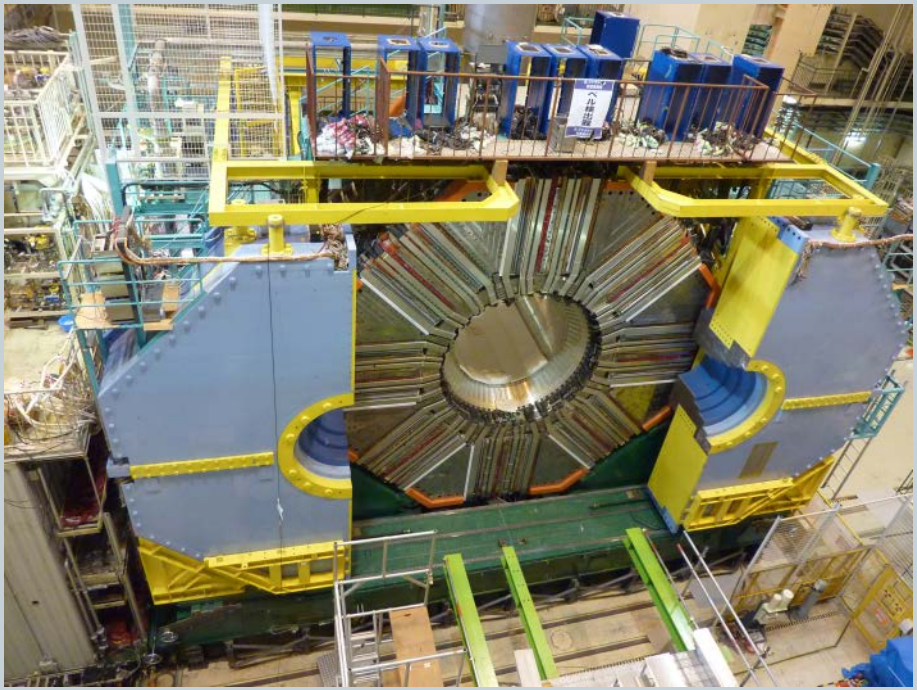


Vertex Detector
2 layers DEPFET + 4 layers DSSD
Vertex resolution improved by order of magnitude: Separate charm/uds

e+ (4GeV)

- RPC test stand at IU to test electronics: E. Zarndt, S. Arnold

Belle II Status



Summary

- Breakthrough Measurements of Proton Structure underway: How does QCD work inside the Nucleon?
- Di-hadron Correlations best way to access transversity in p+p, SIDIS needed to describe spin structure of the proton, derive tensor charge
- Corresponding Fragmentation Functions measured at Belle
  - IFF, Collins in Pions, Kaons (underway), spin averaged single, di-hadron Fragmentation functions,

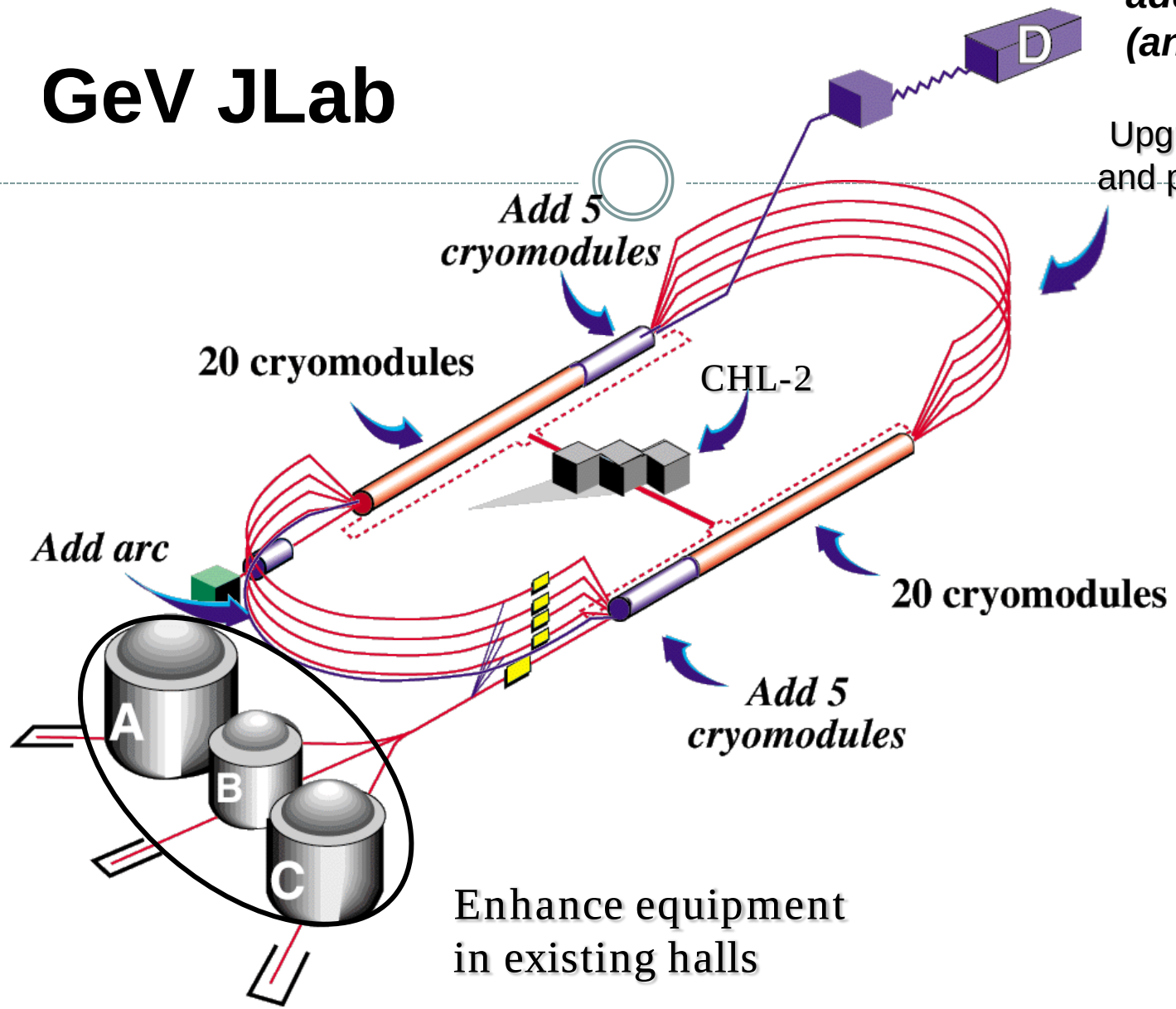
- Outlook
  - Belle II: Continuation of FF measurements with improved Kaon ID and vertex reconstruction
  - Use charm rejection
  - Probe QCD vacuum polarization
  - Measure transverse momentum dependent spin dependent and spin averaged fragmentation functions
  - Precision measurements at Belle (II) crucial for forthcoming measurements at BNL, Jlab, CERN

THANK YOU!

Questions?

- Backup

12 GeV JLab


D
add Hall D
(and beam line)
Upgrade magnets
and power supplies
Add 5
cryomodules
20 cryomodules
CHL-2
Add arc
20 cryomodules
Add 5
cryomodules
A
B
C
Enhance equipment
in existing halls

12 GeV JLab

add Hall D (and beam line)

Upgrade magnets and power supplies

Add 5 cryomodules

20 cryomodules

CHL-2

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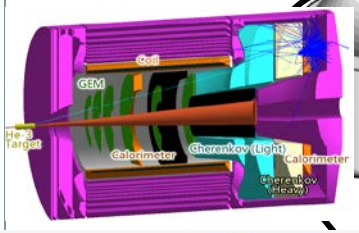
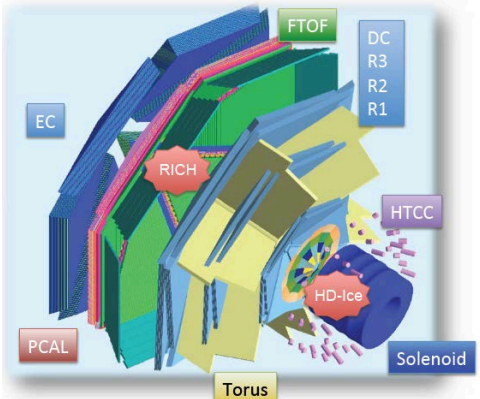
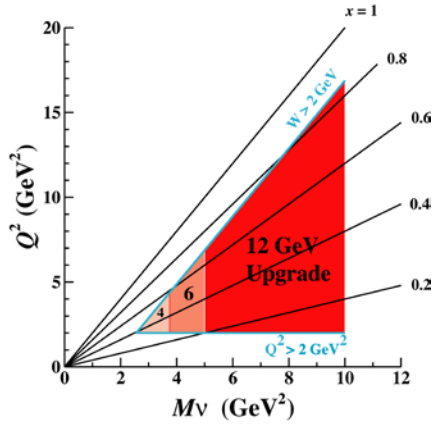
20 cryomodules

Add 5 cryomodules





Enhance equipment in existing halls

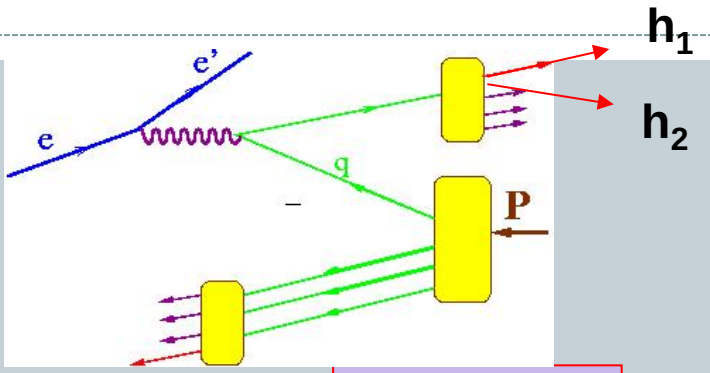


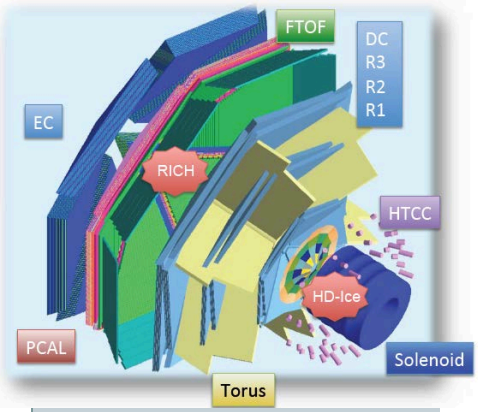
High Luminosity
Access to valence quarks

DIS up to x~0.8
SIDIS, x~0.55

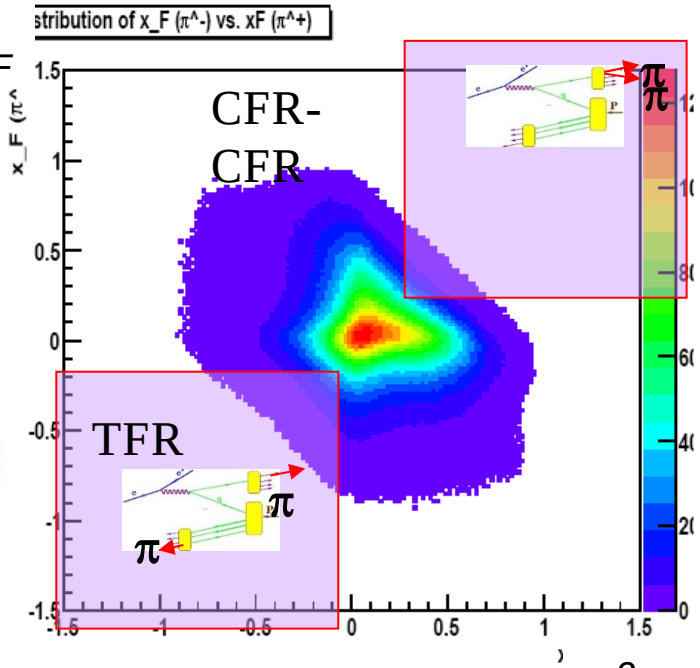
Di-hadron Correlations at CLAS

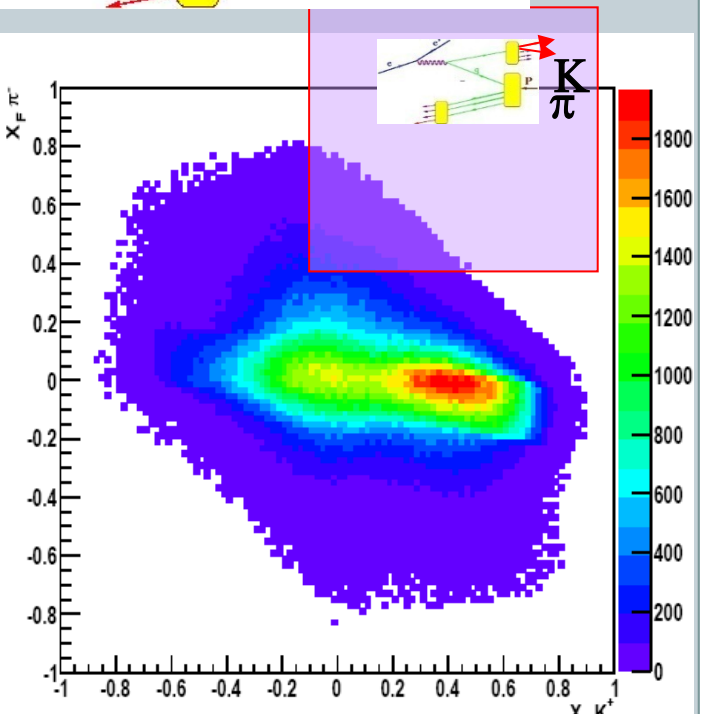
- Di-hadron correlations at CLAS to extract higher twist distribution functions and transversity (with new target)
- Need for πK IFF to exclude target Fragmentation (Belle!)





x^1_F





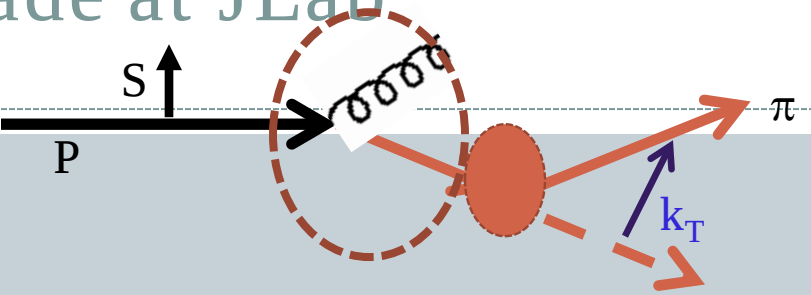
x^2_F

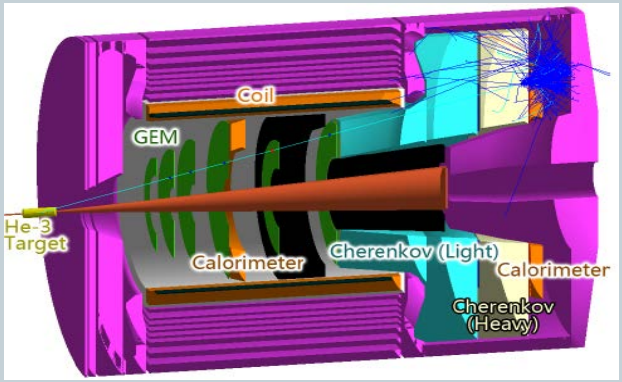
Plots from H. Avakian

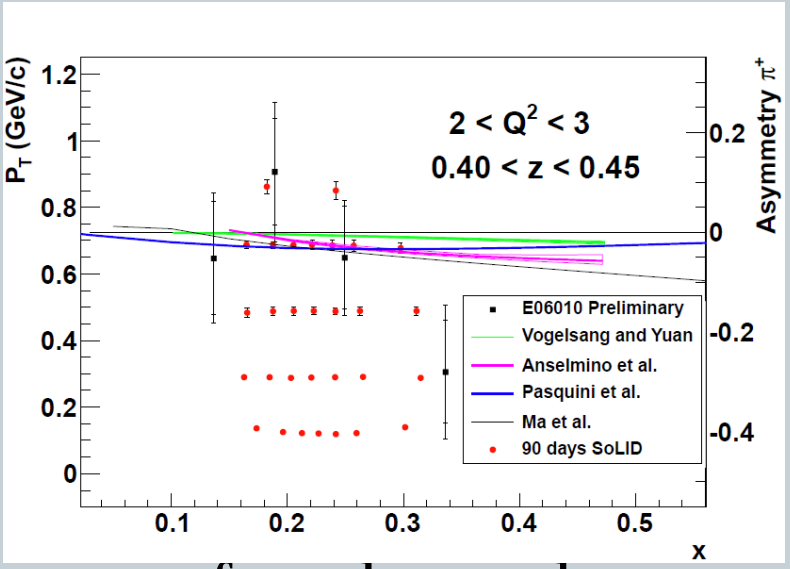
Dihadron sample defined by SIDIS cuts+x_F>0 (CFR) for both hadrons

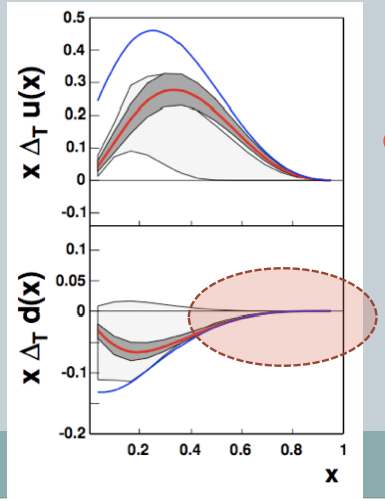
x_F - momentum in the CM frame

Transversity at high x from polarized He3 at SoLID with 12 GeV Upgrade at JLab









- Precise measurement of p_T dependent Collins effect
  - Needs precise measurement of Collins and spin averaged p_T dependent fragmentation functions

Collins Extraction of Transversity: model dependence from Transverse Momentum Dependences!

July 8th

transversity

Collins FF

$$A_{UT}^{Collins} = \frac{\sum_q e_q^2 \int d\phi_S d\phi_h d^2k_\perp h(x,k_\perp) \frac{d(\Delta\sigma)}{dy} H_{1,q}^{\perp}(z,p_\perp) \sin(\phi_S + \phi + \phi_q^h) \sin(\phi_S + \phi_h)}{\sum_q e_q^2 \int d\phi_S d\phi_h d^2k_\perp q(x,k_\perp) \frac{d(\Delta\sigma)}{dy} D_q^h(z,p_\perp)}$$

quark pdf

hadron FF

$k_\perp$ *transverse quark momentum in nucleon*

$p_\perp$ *transverse hadron momentum in fragmentation*

Anselmino, Boglione, D'Alesio, Kotzinian, Murgia, Prokudin, Turk
Phys. Rev. D75:054032,2007

The transverse momentum dependencies are still unknown

Need p_T dependent FFs from Belle to extract transversity and test TMD framework